Preliminary Report on Super Composite Beam and Split Cylinder Experiments

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

OBJECTIVES

These experiments had two main objectives: (1) explore and demonstrate whether the bending-extension (b-e) coupling effect of graphite/epoxy two-layered cross-ply laminate has the potential to substantially improve (e.g., reduce fundamental natural frequencies of) low-frequency, wall-driven composite projectors (such as the slotted cylinder projector), and (2) provide experimental data to confirm theoretical predictions (made with previously derived analytical solutions) on b-e coupled composite beams with simple supports.

SYNOPSIS

Vibration tests were conducted on the flat and curved shapes of bare-beam and actuator-beam specimens, with two-layered and near-symmetric graphite/epoxy cross-ply laminated composites. All bare-beam specimens were tested with free vibration, whereas all actuator-beam specimens were tested with forced vibration. Additionally, all flat specimens were tested in both the simply-supported and the free-free boundary conditions, whereas all curved specimens were tested only in the free-free boundary conditions (due to the setup of the current testing fixtures for simple supports).

Excellent data were obtained from all bare-beam specimens: (a) For beams with simple supports, the average experimental data on the fundamental (natural) frequency and the relative fundamental frequency obtained from the flat specimens were within 1.45% of the theoretical predictions made by the available analytical solutions. (b) For beams with free-free supports, the average experimental data on the relative fundamental frequency obtained from the flat and curved specimens were nearly identical; also, they were practically the same (with a maximum difference of 0.98%) as that of the simply-supported flat specimens. (c) All experimental data clearly demonstrated that the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate substantially reduced (by 38.3 to 38.9%) the fundamental frequency of near-symmetric composite specimens with simple or free-free supports.

Among the actuator-beam specimens, only a few yielded reportable data, since the others may need to be refabricated and retested due to suspected poor bonding between the actuator and the composite of the specimens. Fortunately, excellent data were obtained from the fully-bonded specimens: (a) For beams with simple supports, the experimental data on the fundamental frequency obtained from two flat two-layered cross-ply laminated actuator-beams with different actuator/beam thickness ratios were within 1.80% of the theoretical predictions made by the available analytical solutions. (b) For beams with free-free supports, the experimental data obtained on the relative fundamental frequency of two curved actuator-beam specimens with an actuator/beam thickness ratio of 1.0 clearly demonstrated the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate to substantially reduce (by 19.2%) the fundamental frequency of near-symmetric specimens; the reduction was within 2.28% of the prediction with the available analytical solutions for simply-supported flat actuator-beams with an actuator/beam thickness ratio of 1.0.

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1. INTRODUCTION

It is well known that the N-layered regular (equal thickness layers) antisymmetric cross-ply laminate possesses bending-extension (b-e) coupling properties (Whitney & Leissa, 1969; Jones, 1973, 1975; Whitney, 1987). The largest coupling occurs at N = 2 (two-layered cross-ply (macro-) laminate), whereas the coupling vanishes as N (even number) approaches infinity (homogenized or near-symmetric cross-ply laminate). For such a b-e coupled composite laminate, the b-e coupling properties reduce its stiffness and fundamental (natural) frequencies, as compared with the near-symmetric cross-ply laminate having a difference only in the ply stacking sequence.

As part of his efforts in advanced engineering development for ocean surveillance, Dr. Po-Yun Tang of the Space and Naval Warfare Systems Center, San Diego (SSC San Diego) conducted theoretical studies to determine the potential use of such properties in making super-performance low-frequency composite projectors (Tang, 1995a, 1995b, 1996). Dr. Tang developed consistent classical beam and plate actuation theories for antisymmetric cross-ply laminated beams and split cylindrical shells bonded with actuator(s), properly accounting for the b-e coupling properties of the laminate and the stiffness and density of the (relatively) thick actuator(s). These theories were then used to obtain closed-form (i.e., analytical) solutions for simply-supported b-e coupled composite beams and split cylinders, bonded with actuator(s) and subjected to induced strain actuation or free vibration. These analytical solutions predicted that substantial bending deformation increases and fundamental frequency reductions could be found on simply-supported actuator-beams and actuator-shells due to the b-e coupling properties. For example, 25 to 60% bending deformation increases and 20 to 40% fundamental frequency reductions were discovered for graphite/epoxy two-layered (vs. near-symmetric) cross-ply laminated beams and split cylinders bonded to one side with a lead zirconium titanate (PZT) actuator.

In FY 96, experimental investigations were conducted to confirm theoretical predictions on b-e coupled composite beams with simple supports. A literature review of the relevant experimental studies for the b-e coupled composites found that little data existed: (a) Tsai (1964) extensively studied stiffness of two-layered and three-layered cross-ply laminates made of glass/epoxy. (b) Whitney, Browning, and Mair (1974) studied stiffness of graphite/epoxy angle-ply laminate. (c) No vibration data were available on any b-e coupled composite laminate. SSC San Diego then planned a program of controlled experiments on both bare-beams and actuator-beams made of graphite/epoxy cross-ply laminates. The program included the static bending and free vibration tests of simply-supported graphite/epoxy two-layered and near-symmetric cross-ply laminated (bare) beams and (bare) split cylinders, and the induced strain actuation and free vibration tests of the above-mentioned beams and split cylinders bonded with a PZT actuator to one side of the beams and the concave side of the cylinders, respectively.

Finally, San Diego State University (SDSU) was contracted[*] to fabricate specified test specimens (Principal Investigator: Dr. James Burns) and to conduct planned static and dynamic tests (Principal Investigator: Dr. Chen Liang) to obtain data required for comparisons with theoretical predictions.

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[*] For details of the contracted experimental program, contact Po-Yun Tang for his statement of work written in FY 96, "Super Composite Beam and Split Cylinder Experiments," (Contract Number: N66001-92-D-0092; Delivery Order Number: 12).

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Unfortunately, the death of Dr. Liang caused a major setback to the project. Dr. Burns attempted to complete the remaining contracted work at no additional cost to the government.

In FY 97 and FY 98, both SSC San Diego and SDSU struggled to make progress under the constraints of no funding. SDSU fabricated most of the specimens and started a limited number of rudimentary free vibration tests on beam specimens. SDSU found that (a) testing fixtures for simple supports required substantial modifications; (b) these test specimens were easier to test in the free-free boundary conditions than the planned simply-supported boundary conditions; and (c) these specimens yielded encouraging results only in the free-free boundary conditions. Since the free-free boundary conditions were exactly those for an operating slotted cylinder projector, SSC San Diego agreed to have SDSU run tests both in the free-free and the simply-supported boundary conditions.

However, both SSC San Diego and SDSU realized that funding was the key to real progress. Thus, in FY 99, SSC San Diego granted SDSU additional funding to complete the remainder of the super composite beam and cylinder experiments.[*] Tests were jointly conducted by SSC San Diego and SDSU.

This report documents the super composite beam and split cylinder experiments that were conducted so far. Chapter 2 describes the fabrication of all test specimens. Chapter 3 gives the details for all vibration tests conducted. Chapter 4 presents the testing results on all bare-beam specimens and five[**] fully-bonded actuator-beam specimens tested in either the simply-supported or the free-free boundary conditions. Chapter 4 also compares the theoretical predictions (made by SSC San Diego with the above-mentioned analytical solutions) and the testing results of the simply-supported flat bare-beam and fully-bonded actuator-beam specimens. Chapter 5 summarizes and concludes the report.

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[*] For details of the modified contracted experimental program, contact Po-Yun Tang for his statement of work prepared in FY 99, "Super Composite Beam and Split Cylinder Experiments" (Contract Number: N66001-97-D-5028; Delivery Order Number: 33).

[**] As will be explained in subsection 4.2.1, the other nine of the 14 actuator-beam specimens were probably poorly bonded at testing and might need to be refabricated and retested in the future to yield reportable data. Therefore, this report is labeled as preliminary.

2. FABRICATION OF TESTING SPECIMENS

Flat and curved (i.e., 180° split circular cylindrical shell) shapes of bare-beam and actuator-beam specimens (with nominal surface length of 10") were planned for fabrication. Graphite/epoxy two-layered and near-symmetric (i.e., homogenized) cross-ply laminates were used. The basic flat laminated beam had nominal dimensions of 10" (length) x 1.65" (width) x 0.2" (thickness), while the basic curved laminated beam had nominal dimensions of 3.18" (inner radius) x 1.65" (width) x 0.2" (thickness). The two-layered macro-laminate,[*] and near-symmetric laminate,[**] respectively, had $((0/90)_{16}, 0)$ and $(0_{16}/90_{16})$) ply constructions (i.e., stacking sequences) where the 0° axis was the long axis of the laminates. The bare-beams were basic laminated beams without any actuator bonded to them. The flat actuator-beams were fabricated from the basic flat laminated beams with a PZT (PZT-4) actuator fully bonded (at room temperature) to one side of the 0° layer of the beams in two actuator/beam thickness ratios of 0.5 and 1.0. The curved actuator-beams were fabricated from the basic curved laminated beams with a PZT (PZT-4) actuator fully bonded (at room temperature) to the concave side of the 0° layer of the curved beams in two actuator/beam thickness ratios of 0.5 and 1.0. As summarized in Table 2.1, there were 12 groups of testing specimens planned for fabrication. This chapter describes the fabrication of durable tooling, bare-beam specimens, and actuator-beam specimens, and summarizes the testing specimens completed by SDSU.

Table 2.1. Planned bare- and actuator-beam specimens (2 duplicates, 24 total) by SSC San Diego.

Beam Type (Laminate Nominal Dimensions)	Actuator/Beam Thickness Ratio (PZT Thickness)			Number of Layers in the Laminate
Flat Beam (10" x 1.65" x 0.2")	0.0 (bare)	0.5 (0.1")	1.0 (0.2")	2, 33
Curved Beam (3.18" inner radius x 1.65" x 0.2")	0.0 (bare)	0.5 (0.1")	1.0 (0.2")	2, 33

2.1. TOOLING

For fabricating the specimens, the following durable tooling was fabricated:

1. Flat tooling

    a. One 14" x 0.125" aluminum base plate

    b. One 13" x 13" x 0.0625" aluminum cover sheet

    c. Four 13" x 0.5" x 0.100" aluminum edge strips

    d. Four 12" x 0.5" x 0.100" aluminum edge strips

    e. One 13" x 13" x 0.750" plywood backing board

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[*] Throughout this report, "two-layered cross-ply laminate," "two-layered macro-laminate," and "two-layered composite" are used interchangeably.

[**] Throughout this report, "near-symmetric cross-ply laminate," "near-symmetric laminate," and "near-symmetric composite" are used interchangeably.

2. Curved macro-ply tooling

   a. One female lay-up tool cut into an 8" x 4" x 2" block of aluminum:
original radius 3.283" x 2" wide; final radius 3.383" x 2" wide

   b. One male lay-up tool: 3.183" in radius x 2" wide

   c. One male lay-up tool: 3.283" in radius x 2" wide

   d. One 8" x 2" x 0.125" aluminum base plate

It should be noted that multiple coats of liquid mold release were applied to the surface that may come in contact with the lay-up tool or the resin that may flow away. Adequate mold release prevents the cured beams from adhering to the lay-up tool.

2.2. BARE-BEAMS

2.2.1. Composites Fabrication

A vacuum-curable graphite/epoxy prepreg system, 3M Scotchply SP377 CU1,[*] was used to produce all composite test specimens and prototypes. The system is a 3M-manufactured low-energy-cure prepreg containing AS4 fibers. The use of this system should minimize residual stress and radial spring-in due to its low cure temperatures. Only the amount of material for the planned lay-up was cut from the roll. Prepreg squares were allowed to reach room temperature before lay-up.

All flat bare-beam composite laminate specimens were fabricated at SDSU by using press-heated vacuum coffins. All curved bare-beam laminate specimens were produced in a hot press on CNC-machined matched aluminum tooling. The near-symmetric flat and curved laminates were press-cured in one operation, whereas the two-layered macro-laminates were cured as separate macro-lamina and then bonded together with unfilled room-temperature-cure, two-part epoxy. Trimming to final dimensions was accomplished by using a table saw fitted with a diamond abrasive blade.

2.2.2. Flat Laminate Lay-Up Procedures

a. Macro-Lamina

Instructions:

Place the 0.125" aluminum base plate on a flat table with the mold release on the up facing surface. Remove the paper backing from one side of a prepreg square and place the exposed surface onto the tool plate. One inch of the tool plate should be left exposed around the prepreg. With a paper towel on top of the plastic backing, firmly smooth the newly applied layer. Remove the plastic backing on the prepreg that was just applied to the tool plate. Be careful not to pull up the prepreg with the plastic. Avoid touching any exposed prepreg surfaces. Remove the paper backing from a second prepreg square. Lay the second square directly on top of the first square with the fiber direction of the section parallel to the first. Be sure not to trap any bubbles between the layers. Firmly smooth down the new layer and then remove the plastic backing. Continue applying squares until 16 layers have been laid down. All fibers should be parallel to the first layer. Place a 12" edge strip on parallel sides of the lay-up square and a 13" edge strip on the other two sides. The edge strips should provide a 0.100" high rim around the lay-up. On top of this rim and the prepreg lay-up, place the cover sheet with the

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[*] For complete property data, see Appendix A of SDSU's first report on the composite fabrication (Dinges, 1997).

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mold-released surface facing down. Place the plywood backing board on top of the cover sheet. Carefully place this mold and lay-up arrangement into a vacuum coffin. Cover the mold with gauze cloth and close the vacuum coffin. Apply a vacuum to the coffin to remove air and volatiles while curing.

b. Near-Symmetric Laminates

Instructions:

Place the 0.125" aluminum base plate on a flat table with the mold release on the up facing surface. Remove the paper backing from one side of a prepreg square and place the exposed surface onto the tool plate. One inch of the tool plate should be left exposed around the prepreg. With a paper towel on top of the plastic backing, firmly smooth the newly applied layer. Remove the plastic backing on the prepreg that was just applied to the tool plate. Be careful not to pull up the prepreg with the plastic. Avoid touching any exposed prepreg surfaces. Remove the paper backing from a second prepreg square. Lay the second square directly on top of the first square with the fiber direction of the section perpendicular to the first. Be sure not to trap any bubbles between the layers. Firmly smooth down the new layer and then remove the plastic backing. Continue applying squares with the fiber direction perpendicular to the previous layer. Lay down 33 prepreg squares in this manner. Be certain that the fiber direction of the top layer is parallel to the first layer. Place a 12" edge strip on parallel sides of the lay-up square and a 13" edge strip on the other two sides. The edge strips should provide a 0.100" high rim around the lay-up. On top of this rim and the prepreg lay-up, place the cover sheet with the mold-released surface facing down. Place the plywood backing board on top of the cover sheet. Carefully place this mold and lay-up arrangement into a vacuum coffin. Cover the mold with gauze cloth and close the vacuum coffin. Apply a vacuum to the coffin to remove air and volatiles while curing.

2.2.3. Flat Laminate Curing Process

Instructions:

Preheat only the bottom platen of the hot press to 275 °F. Place the metal side of the vacuum coffin onto the heated platen. Lay 2-ft long 2" x 4" boards edge-wise diagonally across each corner of the vacuum coffin to apply pressure from the top platen to the vacuum coffin to prevent heat warping. Cure laminates for 90 minutes at 275 °F under vacuum. After 90 minutes, remove the vacuum coffin from the hot press and allow the tool and laminate to cool under vacuum. Once the tool and laminate have been cooled, remove them from the vacuum coffin. Remove the cured laminate from the tool and be careful not to scratch the lay-up tool. Discard any gauze that has absorbed resin. Clean the lay-up tool of any resin or fiber residue.

2.2.4. Flat Macro-Laminate Bonding

Instructions:

Scuff and clean one side of two 12" x 12" 16-layer unidirectional macro-laminates. Place the laminates on a flat table with the prepared side facing up. Mix enough two-part epoxy glue to apply a thin coat over the prepared side of each laminate. Spread epoxy glue onto the prepared side of the two laminates only. Place one laminate on the aluminum base plate with the epoxy glue side of the laminate facing away from the base plate. Place the other laminate on top of the laminate on the base plate so that the glue-smeared sides are in contact with each other. The laminates should be arranged so that their fiber directions are perpendicular to each other. Place the cover sheet over the laminates and carefully put the arrangement into the cool press. Apply pressure to the laminate at room

temperature until the epoxy glue has cured. Remove the arrangement from the cool press once cured. Remove the laminate from the tooling and clean the tool if any epoxy has stuck to it.

2.2.5. Cutting Flat Laminates

Instructions:

Cut flat laminates into 1.65" strips using a circular diamond saw on a table saw. Cut the near-symmetric laminates so that the long axis of the cut is parallel to the fiber direction on the two out-side layers. That is, the top and bottom layers of the near-symmetric laminates should be $0°$ layers. Cut the bonded macro-laminates into 1.65" strips using a circular diamond saw.

2.2.6. Curved Macro-Ply Laminate Lay-Up[*]

This follows the same general procedures as for other curved laminates, except that each $0°$ macro-ply is laid up and cured before the female lay-up tool is machined to a new inside radius. With the new radius, the tool can be used to lay up and cure all the $90°$ macro-plies. This procedure prevents thermal residual stresses (associated with unbalanced laminates of this type) from deforming the intended geometry.

a. Prepreg Preparation

Instructions:

Cut out 12" x 12" squares from the 12" wide prepreg roll. Cut 2" strips from the 12" squares. Cuts should be made parallel to the fiber direction for the $0°$ layers and perpendicular to the fiber direction for the $90°$ layers. Cut only enough prepreg material from the roll to make the desired laminate. Allow prepreg to come up to room temperature before applying it to the mold.

b. $0°$ Curved Macro-Ply Lay-Up

Instructions:

On a flat table, place the small male tool (properly mold-released and attached to the small base plate) with the arched surface facing up. Remove the paper backing from one of the 12" x 2" $0°$ strips. Place one of the 2" edges touching the base plate and smooth the strip over the arch so that the extra 2" overshoot the arch on one side only. Trim the extra 2" from the strip with a razor blade. Remove the plastic backing from the strip and be careful not to pull the strip from the tool. Remove the paper backing from a second strip and lay it over the first strip already on the tool. As with the first, start from one end and smooth the strip over the tool while being careful not to trap any air bubbles between the layers. Trim the excess strips that may be left so that the end of the strips does not drape onto the base plate. Carefully remove the plastic backing from the layer that was just applied. Repeat the process of applying layers and trimming the excess until 16 layers have been laid down. Cover the male tool and prepreg layers with the small female tool arch facing down.

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[*] For curved laminates, we only present their lay-up procedures. Their curing process, macro-laminate bonding, and cutting into 1.65" strips follow essentially the same instructions as those for flat laminates (given in subsections 2.2.3, 2.2.4, and 2.2.5, respectively) and therefore are not presented here.

c. 90° Curved Macro-Ply Lay-Up

Instructions:

On a flat table, place the large male tool (properly mold-released and attached to the small base plate) with the arched surface facing up. Remove the paper backing from one of the 12" x 2" 90° squares. Place one of the 2" edges so that it is aligned with the base plate and smooth the strip over the arch so that the extra 2" overshoot the arch on one side only. Trim the extra 2" from the strip with a razor blade. Remove the plastic backing from the strip and be careful not to pull the strip from the tool. Remove the paper backing from a second strip and lay it over the first strip already on the tool. As with the first, start from one end and smooth it over the tool and be careful not to trap any air bubbles between the layers. Trim the excess strips that may be left so that the end of the strips does not drape onto the base plate. Carefully remove the plastic backing from the layer that was just applied. Repeat the cycles of applying layers and trimming the excess until 16 layers have been laid down. Cover the male tool and prepreg layers with the large female tool arch facing down.

d. Near-Symmetric Curved Macro-Ply

Instructions:

On a flat table, place the small male tool (properly mold-released and attached to the small base plate) with the arched surface facing up. Remove the paper backing from one of the 12" x 2" 0° strips. Place one of the 2" edges so that it is aligned with the base plate and smooth the strip over the arch so that the extra 2" overshoot the arch on one side only. Trim the extra 2" from the strip with a razor blade. Remove the plastic backing from the strip and be careful not to pull the strip from the tool. Remove the paper backing from a second (90°) strip and lay it over the first strip already on the tool. As with the first, start from one end and smooth the strip over the tool and be careful not to trap any air bubbles between the layers. Trim the excess strips that may be left so that the end of the strips does not drape onto the base plate. Carefully remove the plastic backing from the layer that was just applied. Repeat the process of applying layers and trimming the excess until 33 layers have been laid down. Cover the male tool and prepreg layers with the large female tool arch facing down.

2.3. ACTUATOR-BEAMS

Actuator-beams were fabricated by bonding PZT actuator segments to some of the bare-beams described in the last section. These actuator segments were custom-ground and poled by Piezo-Kinetics of Bellefonte, PA, from its 402 PZT material. As illustrated in figure 2.1, the actuators were fabricated in four sizes: nominal thickness of 0.100" and 0.200" in either rectangular or truncated wedge cross-sections for the inner surfaces of the flat and curved beams, respectively. Upon receipt, SDSU checked the actuator segments for dimensional specifications and cleaned all surfaces with a solvent wipe to aid in bonding. A two-part nickel-filled epoxy (Emerson & Cuming Eccobond®* 64 C—see Appendix A of the SDSU report [Dinges, 1997]) was procured from E. V. Roberts & Associates for use as an electrically conductive bonding agent between the actuator segments. Nickel was used instead of silver due to its lower price and superior resistance to chlorides. Tin-coated copper electrode strips with a nominal thickness and width of 0.006" and 0.100", respectively, were also procured for use as leads to the buses carrying the excitation voltage. These strips were cut to 3.5" lengths. Figure 2.2 shows the electrode strips and buses in assembled curved actuator-beams.

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* Eccobond is a registered trademark of the National Starch and Chemical Company (of which Emerson & Cuming is an integral part).

A.

0.200

1.65

0.100

Ag

POLING DIRECTION

B.

0.200

1.65

0.200

Ag

POLING DIRECTION

C.

0.200

1.65

0.100

0.193

Ag

POLING DIRECTION

D.

0.200

1.65

0.200

0.187

Ag

POLING DIRECTION

UNIT: INCH
402 PZT MATERIAL
STANDARD TOLERANCE:

A
C } ± 0.001 All Dimensions

B
D } ± 0.002 All Dimensions
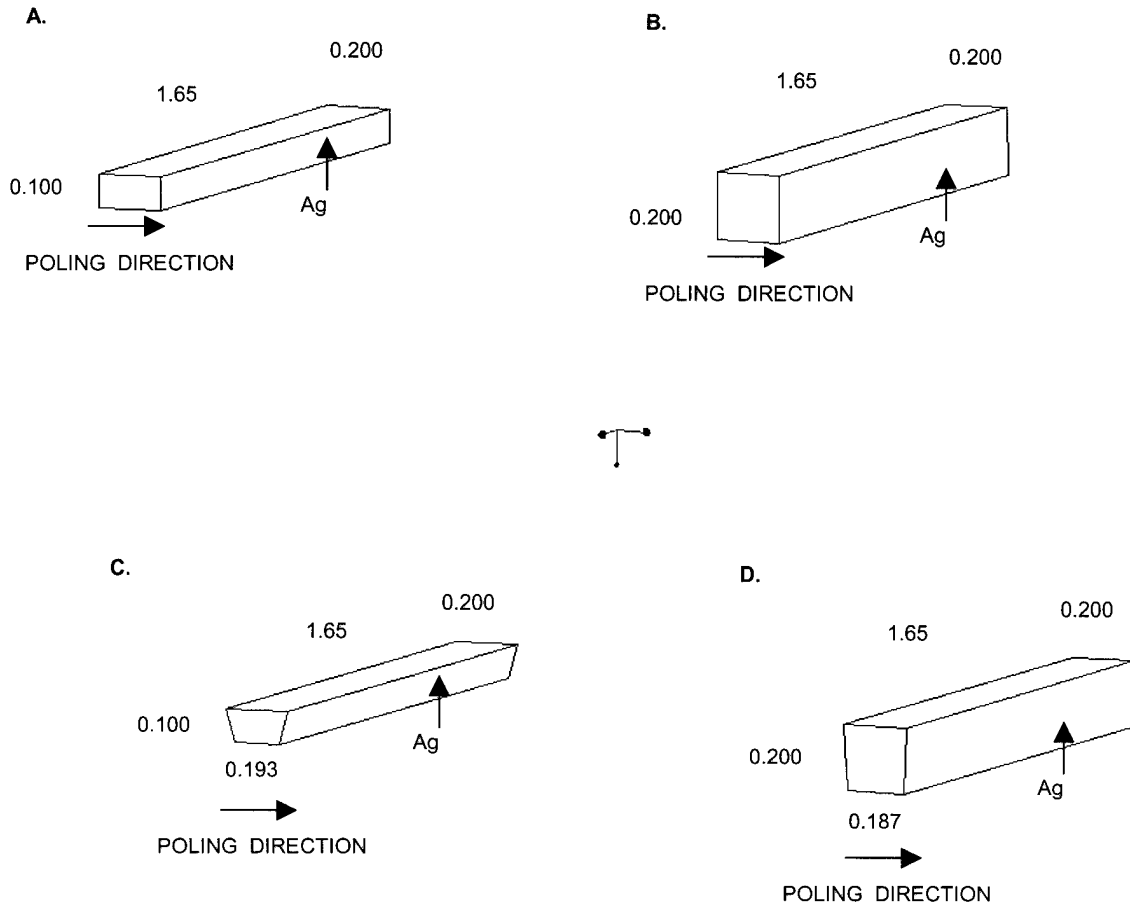
Figure 2.1. Actuator segment geometries.

To aid in the assembly and bonding of flat actuator segments into a single subassembly, a Plexiglas fixture was fabricated and lined with wax paper. Pot-life of the mixed epoxy was approximately 40 minutes. Individual segments and electrode strips were scuffed and solvent-wiped to enhance epoxy bond strength. Segments were pre-marked to indicate poling direction and arranged in alternating back-to-front pairs before bonding began. After the two-part-filled epoxy was mixed (only enough for one beam), it was applied sparingly with a sharp knife in an approximately 1-mil layer to each silvered electrode side of one actuator. An electrode strip was placed on the epoxy layer on one side of the segment, and the actuator was placed in the fixture. The process was repeated for each successive segment until the actuated surface of the beam was covered. Care had to be taken to keep the epoxy layers as close to 1-mil thickness as possible and to use all mixed epoxy before it

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ELECTRODE
STRIP

BUS
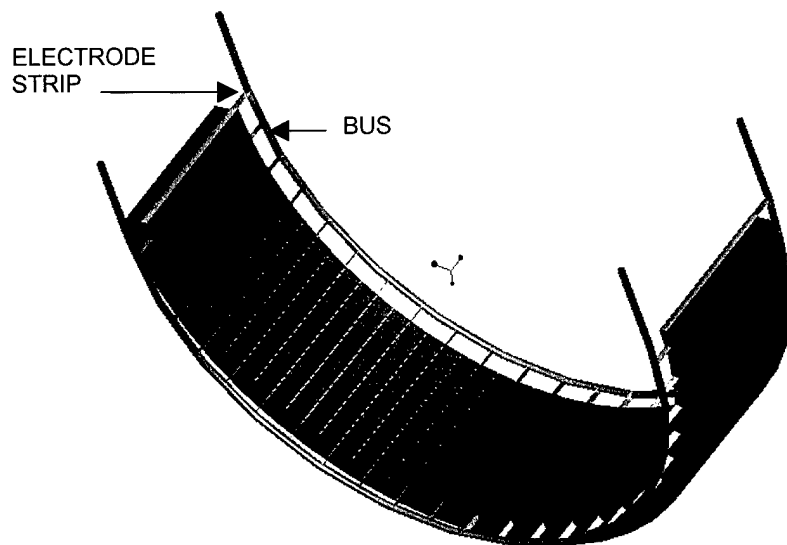
A. ACTUATOR/BEAM THICKNESS RATIO = 0.5

ELECTRODE
STRIP

BUS
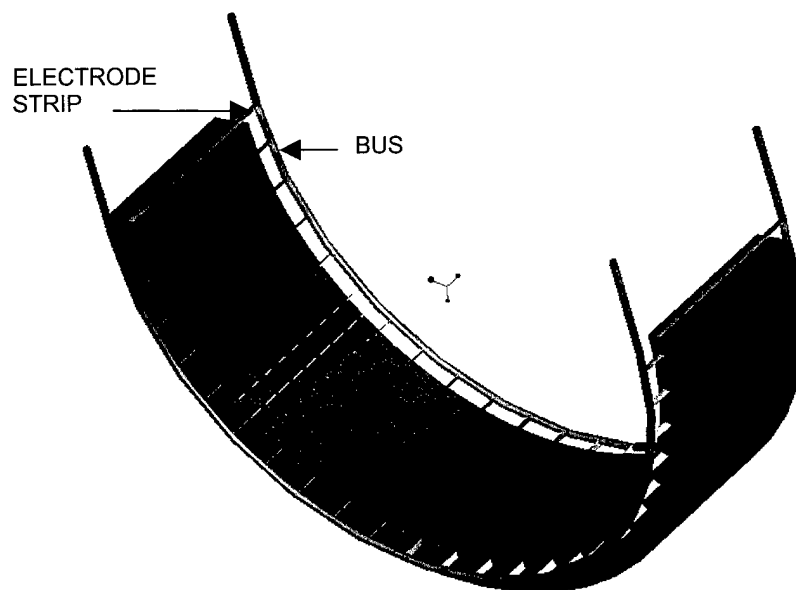
B. ACTUATOR/BEAM THICKNESS RATIO = 1.0

Figure 2.2. Assembled curved actuator-beams.

hardened. Once cured, the assemblies were gently removed from the fixture, scraped to remove excess conductive epoxy, and then bonded to their composite laminates with unfilled room-temperature-cure, two-part epoxy.

Curved actuator subassemblies were fabricated using the female half of the matched tooling holding the composite laminates as a fixture for the actuator segments. Wax paper was again used to

separate the segments from the laminate during cure. Completion of the process followed that for the flat beam assemblies.

The last step of fabricating flat and curved actuator-beam specimens was bus wiring. As shown in figure 2.2, the protruding end of every other electrode strip in the actuator subassembly was wrapped around one 12-gage copper bus wire running the length of one edge of the beam, and the wrap connection was soldered in place. The remaining strips were wrapped and soldered to a second bus running the length of the opposite edge.

2.4. COMPLETED SPECIMENS

Following the plan given in table 2.1 and using the methods described in sections 2.2 and 2.3, SDSU fabricated four flat bare-beam, seven flat actuator-beam, three curved bare-beam, and seven curved actuator-beam specimens (see table 2.2). All bare-beam and some of the actuator-beam specimens were fabricated in FY 96.[*] Table 2.3 assigns each specimen a number for subsequent reference. Figure 2.3 depicts the completed 21 beam specimens.

Table 2.2. Number of bare-beam and actuator-beam specimens fabricated by SDSU.

a. Flat beam specimens

Actuator/Beam Thickness Ratio (PZT Thickness)	Two-Layered	Near-Symmetric
0.0 (Bare)	2	2
0.5 (0.1")	1	2
1.0 (0.2")	2	2

b. Curved beam specimens

Actuator/Beam Thickness Ratio (PZT Thickness)	Two-Layered	Near-Symmetric
0.0 (Bare)	1	2
0.5 (0.1")	3	1
1.0 (0.2")	1	2

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[*] In addition to these beam specimens, in 1996, SDSU also fabricated six ASTM $0°$ and six ASTM $90°$ graphite/epoxy tensile coupons and conducted rudimentary stiffness tests on them. Results were documented in the SDSU report (Dinges, 1997).

Table 2.3. Specimen numbering scheme.

a. Flat beam specimens

Actuator/Beam Thickness Ratio	Two-Layered	Near-Symmetric
Bare	1A, 1B	2A, 2B
0.5	3A	4A, 4B
1.0	5A, 5B	6A, 6B

b. Curved beam specimens

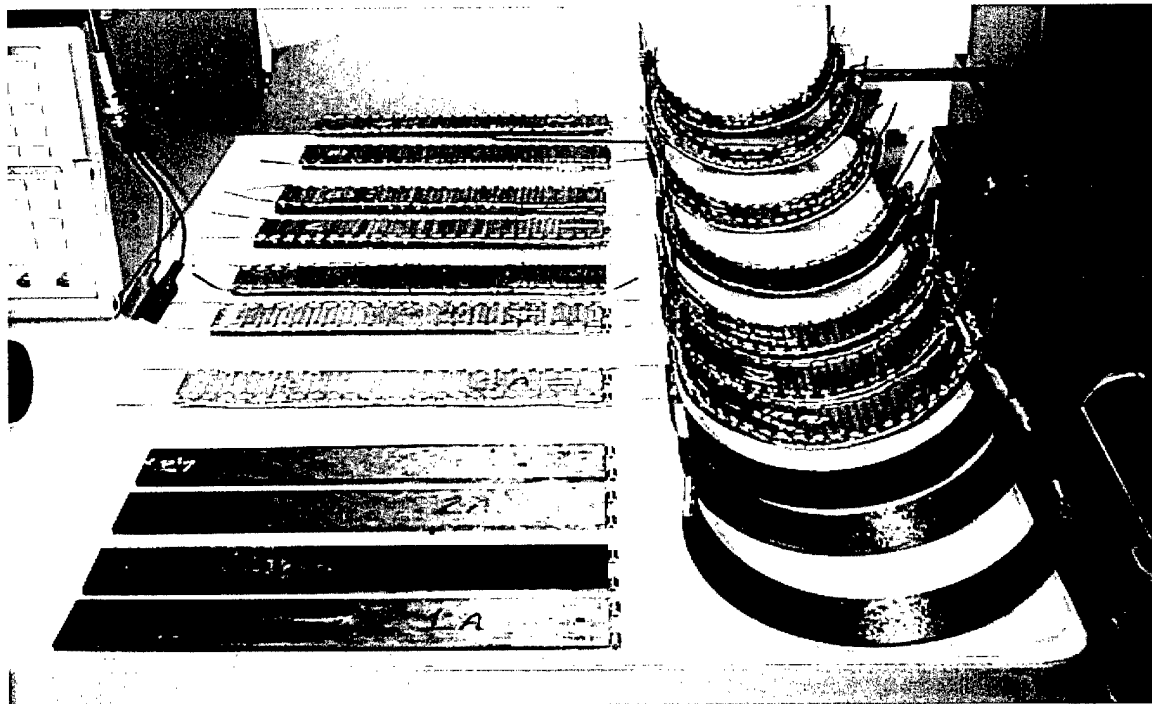| Actuator/Beam Thickness Ratio	Two-Layered	Near-Symmetric
Bare	7A	8A, 8B
0.5	9A, 9B, 10B	10A
1.0	11A	12A, 12B

Figure 2.3. Bare-beam and actuator-beam specimens fabricated by SDSU.

3. VIBRATION TESTS

All vibration tests documented in this chapter were jointly conducted by SSC San Diego and SDSU in 1999 in the High Voltage and Materials Testing Laboratory of SSC San Diego. These tests were conducted on the flat and curved shapes of bare-beam and actuator-beam specimens fabricated by the instructions given in chapter 2. Section 3.1 starts with the instruments used in the vibration tests. Section 3.2 prepares the specimens for testing in the simply-supported and free-free boundary conditions. Section 3.3 introduces the free and forced vibration testing, with vibrations being generated by mechanical and electrical excitations, respectively.

3.1. INSTRUMENTS

Figure 3.1 shows all the instruments, as well as their connectors, used for the vibration tests on the beam specimens. These instruments included a network signal analyzer (Model SR780 manufactured by Stanford Research Systems [SRS]), a preamplifier box (Model P703B of Wilcoxon Research [WR]), and a miniature accelerometer (WR Model TM212S), which were all needed for all vibration tests. The instruments also included a power amplifier (BGW Performance Series 2) and electrical clamp connectors, which were also needed for electrically excited forced vibration tests.
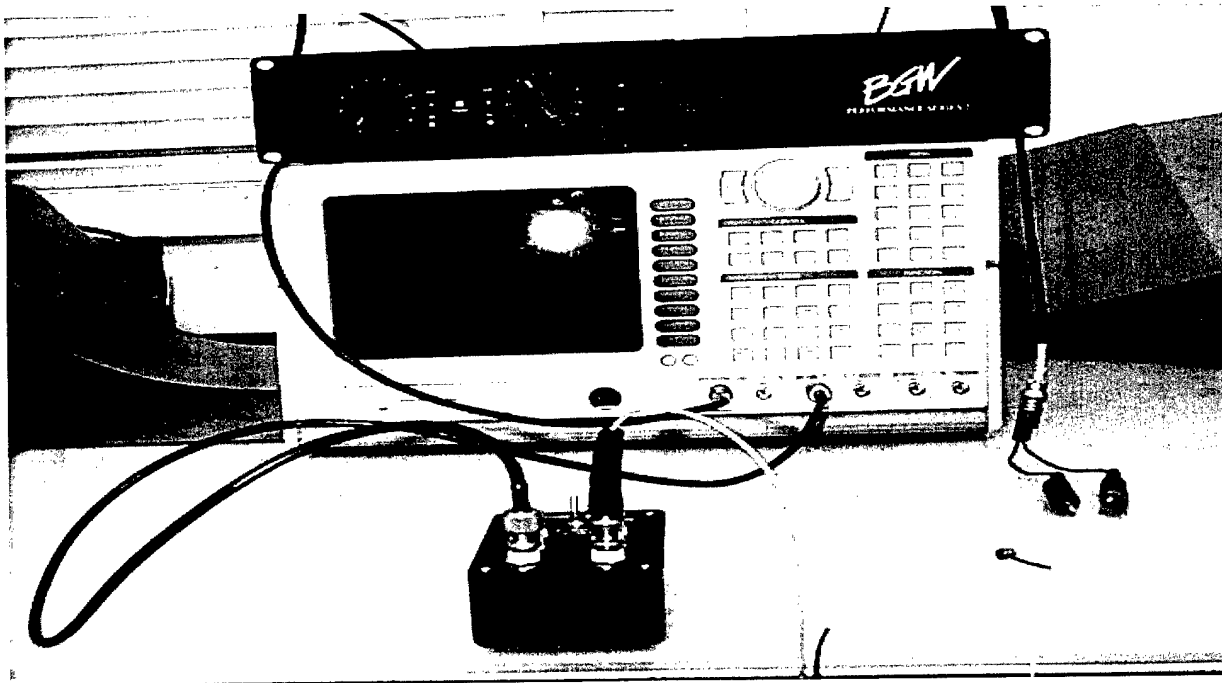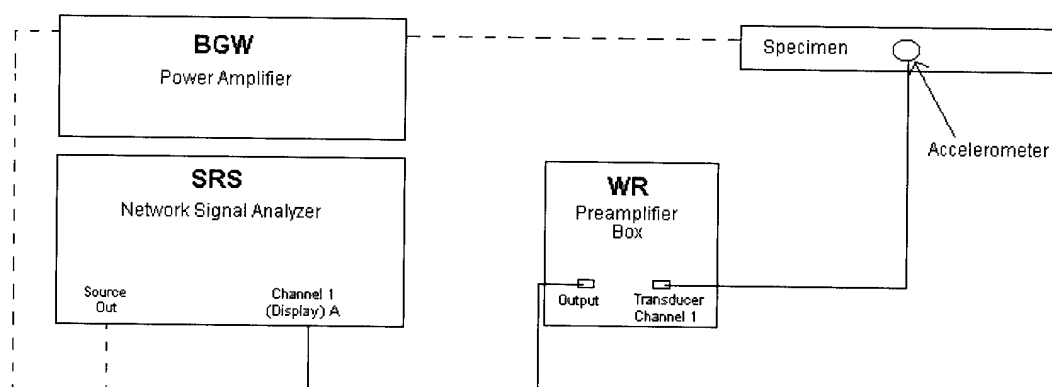

Figure 3.1. Instruments and connectors.

Figure 3.2 depicts the functional diagram for a vibration test, showing the proper connection of various instruments and a specimen. The solid connecting lines alone represent the testing setup for a free vibration test, whereas the solid and broken lines together represent the testing setup for a forced vibration test.

(Note: Diagram not drawn to scale.)

Figure 3.2. Vibration test functional diagram.

The SRS Model SR780 network signal analyzer has two channels for data display and three measurement groups, including the 90-dB dynamic range Fast Fourier Transform (FFT) group for measuring free vibration data and the 145-dB dynamic range Swept Sine group for measuring forced vibration data. The detailed procedures for using the SR780 analyzer to measure data on the fundamental (natural) frequency of the specimens under free and forced vibrations can be found in the operating manual for the analyzer (SRS, 1996) and will not be repeated here.

The WR Model P703B preamplifier box was used to amplify the input signal data so it could be clearly recorded. The WR Model TM212S test and measurement series miniature accelerometer was attached to one surface of a beam specimen to sense the signal of the normal surface displacement, which is at and perpendicular to the surface of the specimen under excitation. The accelerometer is lightweight and compact, and possesses wide dynamic range and frequency response. The accelerometer also includes a mounting adhesive to promote easy placement. The BGW Performance Series 2 power amplifier was needed to operate simultaneously with the other instruments for forced vibration of an actuator-beam specimen. The amplifier was used to supply the power needed for electrically exciting the PZT bonded to the specimen via electrical clamp connectors.

3.2. BOUNDARY CONDITIONS

Preparations of flat beam specimens* for testing in the simply-supported boundary conditions, and both flat and curved beam specimens in the free-free boundary conditions, respectively, are given below in subsections 3.2.1 and 3.2.2.

3.2.1. Simple Supports

Figure 3.3 shows flat bare-beam and actuator-beam specimens in the simply-supported testing fixture with sharp edge and hinged supports (which are detailed in figure 3.4). The following procedures are necessary in preparing a flat specimen in such simply-supported boundary conditions. First,

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* It should be clear, after describing the current testing fixtures for simple supports in subsection 3.2.1, that all curved beam specimens cannot be tested in such testing fixtures. Hence, only flat beam specimens were tested in the simply-supported boundary conditions.

clamp one end of the testing fixture to a fixed foundation to avoid any relative movement of the testing fixture with respect to its foundation during testing. Second, attach the accelerometer to the center of the composite surface of a bare-beam or an actuator-beam specimen, wrapping it tightly with Scotch tape. Third, place the specimen on the fixture, with the pre-glued hinge of the specimen fastened with the hinged support by a pin. (See figure 2.3 for hinges[*] glued to the composite side[**] of flat specimens.) Be sure that the specimen freely rotates at the hinged end and closely contacts the sharp edge support at the other end. Moreover, for an actuator-beam, its copper bus wires may need to be temporarily bent up before placing the specimen on the fixture to avoid any interference of the bus wires with the fixture during testing.
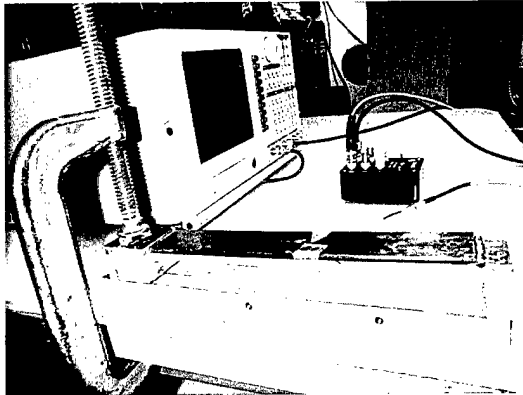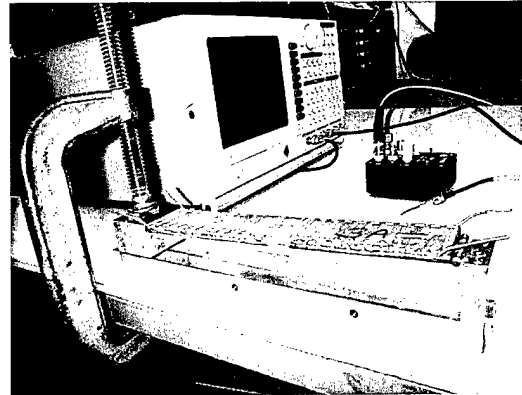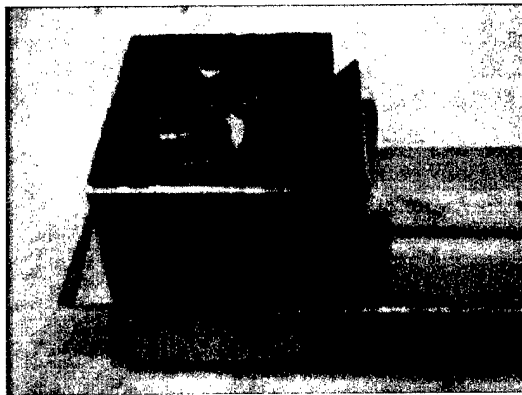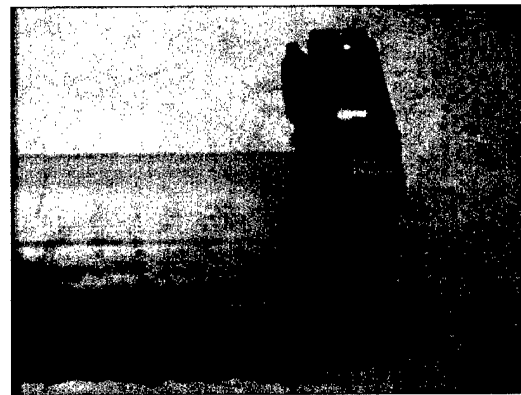

| A. Flat bare-beam | B. Flat actuator-beam |

Figure 3.3. Specimens with the simply-supported edge boundary conditions.

| A. Sharp edge support | B. Hinged support |

Figure 3.4. Details of simple supports.

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[*] It should be noted that these hinges were glued to the flat specimens after all free-free supported tests on these specimens were completed. Although free-free supported tests were conducted before simply-supported tests, we prefer to present the latter first for our purposes.

[**] We found that it was easier and thus chose to glue the hinge on the composite surface rather than the PZT surface of an actuator-beam specimen. This choice combined with the constraint of the hinged end of the fixture led the PZT surface to be the top surface of the actuator-beam specimen when the specimen was placed in the fixture. For a forced vibration testing of the simply-supported specimen, the accelerometer was then attached to the middle of the composite (i.e., bottom) surface, rather than the PZT surface as in the free-free supported tests. However, we found earlier in the free-free supported tests that the testing results on the fundamental frequency were the same, whether the accelerometer was placed on the composite or the PZT surface.

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3.2.2. Free-Free Supports

Figure 3.5 shows flat and curved shapes of bare-beam and actuator-beam specimens with free-free supports. The following procedures are necessary in preparing a flat or curved shape of bare-beam or actuator-beam specimen in the free-free boundary conditions. First, hang two (for the flat specimen) or three (for the curved specimen) pieces of fish line of equal length (about 6 feet) vertically. Be sure to equally space the fish lines, with the outer lines spaced approximately by the length of the flat specimen or the diameter of the curved specimen. Attach a small washer to the lower end of each fish line. Second, attach the accelerometer to the center of a composite surface of the bare-beam specimen or the PZT surface of the actuator-beam specimen, and wrap the accelerometer tightly with Scotch tape. Third, attach all two or three washers to the specimen and hang it with its length at a horizontal position and its width at a vertical position. For any bare-beam specimen, tape the two washers on the outside lines with Scotch tape in the upper respective corners of the composite surface, on the opposite side of the accelerometer. For any actuator-beam specimen, connect the two washers on the outside lines to one of the bus wires of the specimen by passing the wire through the central holes of the washers. Additionally, for any curved specimen, tape the middle washer to the top-middle of the composite surface of the specimen, also on the opposite side of the accelerometer.
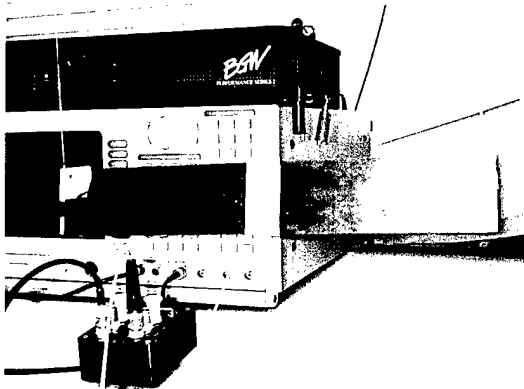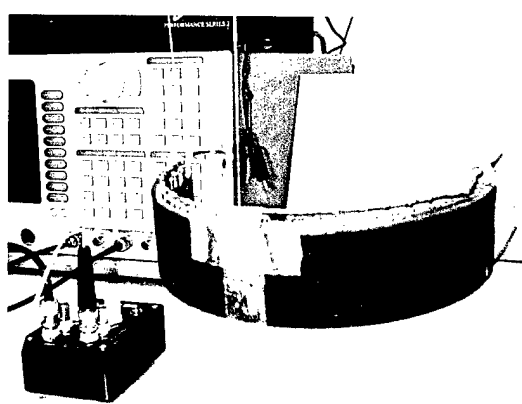

A. Flat bare-beam
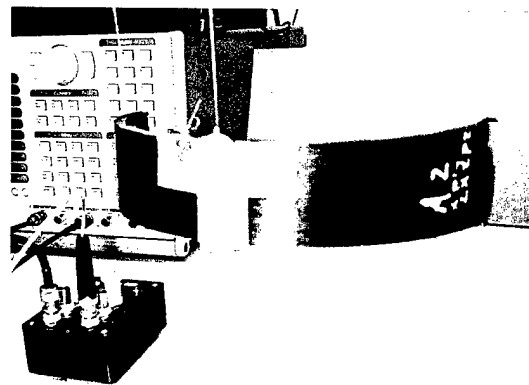
B. Curved bare-beam
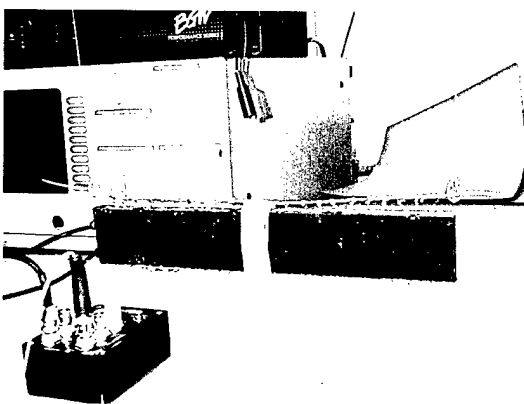
C. Flat actuator-beam

D. Curved actuator-beam

Figure 3.5. Specimens with the free-free boundary conditions.

3.3. VIBRATION METHODS

The next two subsections describe free vibration of a bare-beam specimen and forced vibration of an actuator-beam specimen.

3.3.1. Free Vibration

Free vibrations of a bare-beam specimen in the direction normal to the specimen surface were generated by five different methods of mechanical excitation, all being applied to the center of the specimen surface on the opposite side of the accelerometer. The methods were fingernail flick, soft and hard hits with a large rubber mallet, and soft and hard hits with a small modal hammer.

3.3.2. Forced Vibration

Forced vibration of an actuator-beam specimen in the direction normal to the specimen surface was generated by electrical excitation of the PZT actuator bonded to the specimen. The BGW power amplifier was first connected and turned on. The electrical clamp connectors were then connected to opposite sides of the center of the buses, thereby actuating the PZT to vibrate the specimen.

Figures 3.6, 3.7, and 3.8, respectively, depict the above-described mechanical and electrical excitation methods applied to simply-supported flat beams, free-free supported flat beams, and free-free supported curved beams.
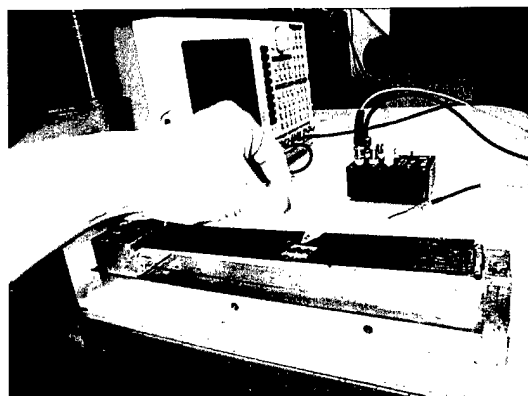
A. Fingernail flick
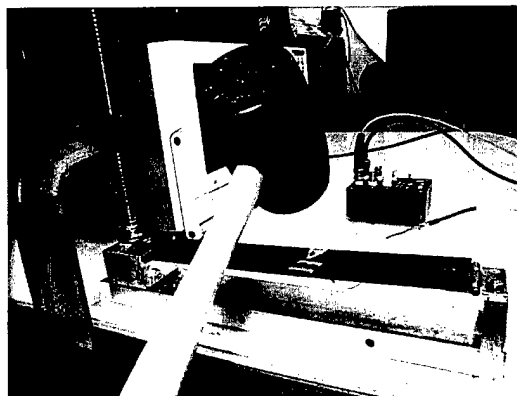
B. Soft or hard hit with a large rubber mallet
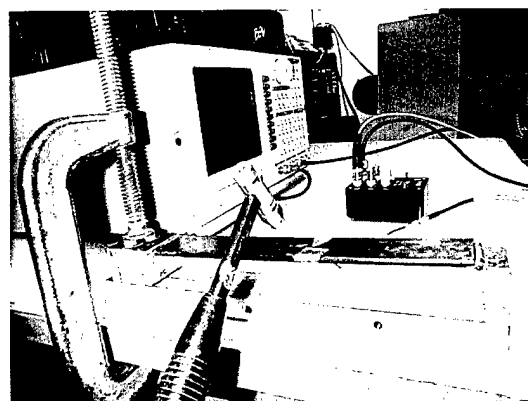
C. Soft or hard hit with a small modal hammer
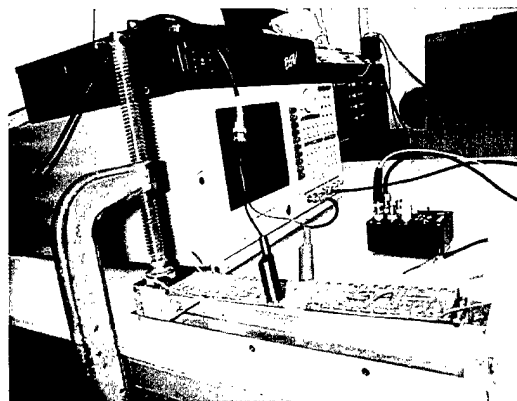
D. Electrical excitation

Figure 3.6. Excitation methods for simply-supported flat beams.
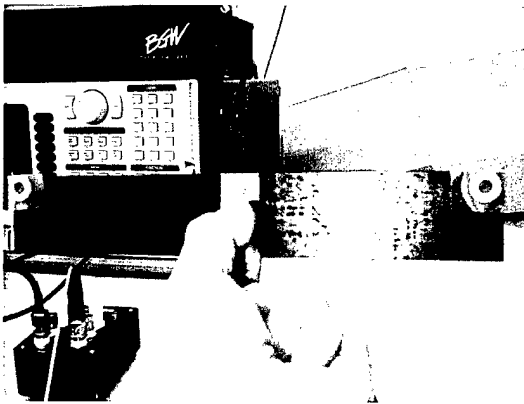
17

A. Fingernail flick

B. Soft or hard hit with a large rubber mallet

C. Soft or hard hit with a small modal hammer

D. Electrical excitation

Figure 3.7. Excitation methods for free-free supported flat beams.

A. Fingernail flick

B. Soft or hard hit with a large rubber mallet

C. Soft or hard hit with a small modal hammer

D. Electrical excitation

Figure 3.8. Excitation methods for free-free supported curved beams.

4. TESTING RESULTS

This chapter presents the vibration testing results on fundamental (natural) frequencies of the flat and curved shapes of graphite/epoxy two-layered and near-symmetric cross-ply laminated bare-beam and actuator-beam specimens that were fabricated by SDSU and that were described i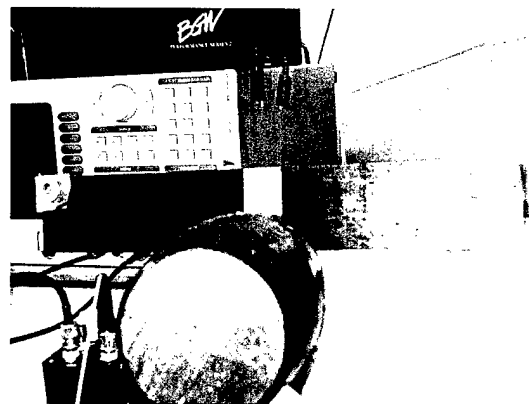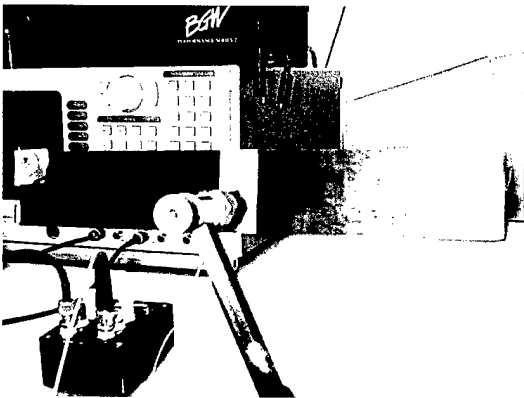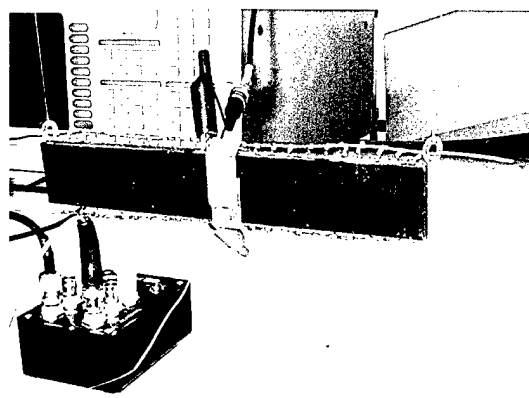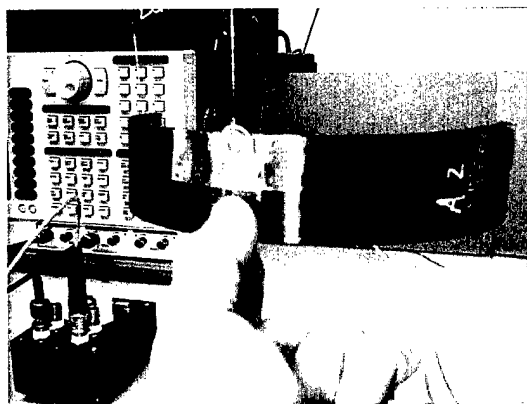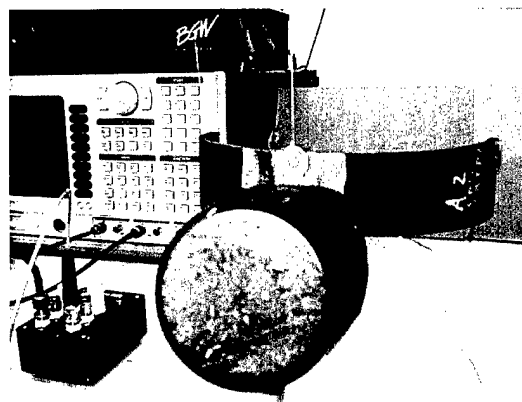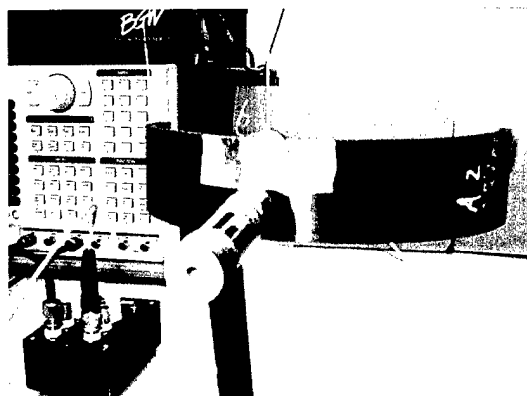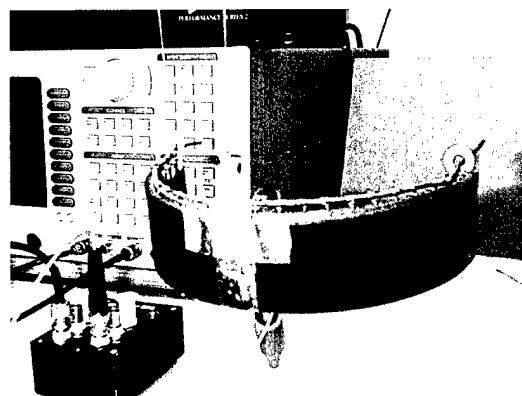n chapter 2. Sections 4.1 and 4.2 document the results for free vibration of the bare-beam specimens and the forced vibration of the actuator-beam specimens, respectively.

4.1. BARE-BEAMS

We obtained excellent data for all bare-beam specimens. Subsection 4.1.1 contains all the free vibration data on flat bare-beam specimens tested in the simply-supported boundary conditions and compares these data with theoretical predictions made by SSC San Diego with previously derived analytical solutions. Subsections 4.1.2 and 4.1.3 contain all the free vibration data on the flat and the curved bare-beam specimens, respectively, tested in the free-free boundary conditions.

4.1.1. Flat and Simply-Supported

Figure 4.1 records the vibration spectra[*] (i.e., signals of normal surface displacements vs. frequencies) of a flat two-layered graphite/epoxy cross-ply laminated bare-beam specimen (specimen 1A) with simple supports and subjected to various free vibrations. The free vibrations were generated by five different methods of mechanical excitation as described in subsection 3.3.1. Figure 4.2 records the vibration spectra of specimen 1B, the duplicate of specimen 1A. Along with these vibration spectra, their respective fundamental frequencies are also identified in figures 4.1 and 4.2. Table 4.1 lists the fundamental frequency data obtained for the two flat two-layered composite bare-beam specimens with simple supports. From table 4.1, we observe that these data are essentially the same with different methods of mechanical excitation and their specimen-to-specimen variations are negligibly small. It should be noted that this observation prevails for all the fundamental frequency data of the flat and curved bare-beam specimens, which will be reported in the remainder of section 4.1. From table 4.1, we also see that the average of the fundamental frequency data on the two two-layered specimens is 149.4 Hz.

Table 4.1. Fundamental frequency (Hz) data of flat *two-layered* graphite/epoxy composite bare-beam specimens with simple supports.

Methods of Mechanical Excitation	Specimen 1A	Specimen 1B
Fingernail Flick	148	150
Large Rubber Mallet—Soft Hit	148	152
Large Rubber Mallet—Hard Hit	148	152
Small Modal Hammer—Soft Hit	148	150
Small Modal Hammer—Hard Hit	148	150

Average Data = 149.4 Hz

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[*] In every spectrum recorded in figures 4.1 to 4.15 of this chapter, the X-axis represents the frequency (in Hz) and is linear in scaling, whereas the Y-axis represents the magnitude of the signal measurement (in dB V_{pk}) and is logarithmic in scaling. The magnitude is simply $(x^2 + y^2)^{0.5}$, where x is the real part and y is the imaginary part of a measurement. Moreover, dB stands for decibel and V_{pk} is the peak voltage.
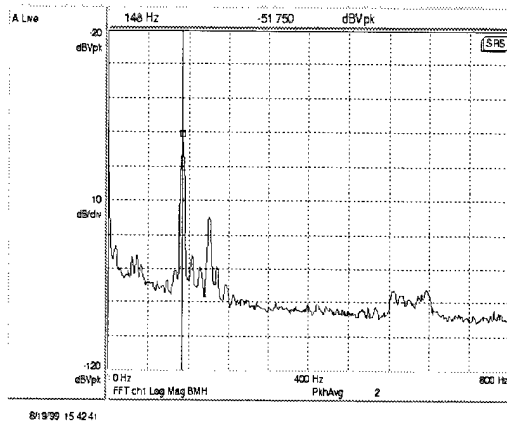
A. Fingernail flick
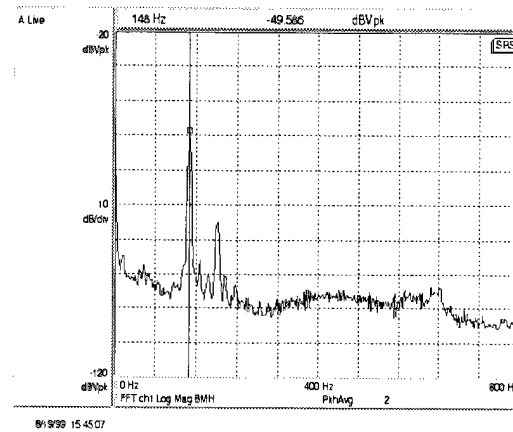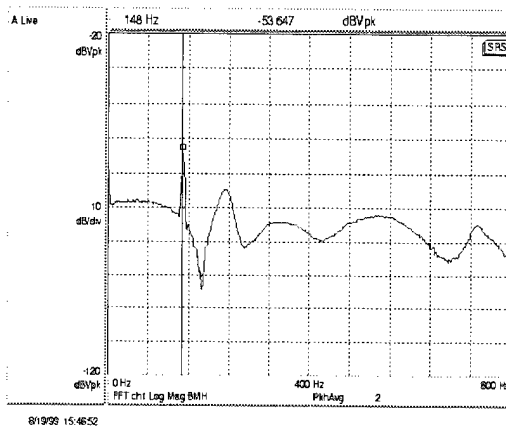
B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet
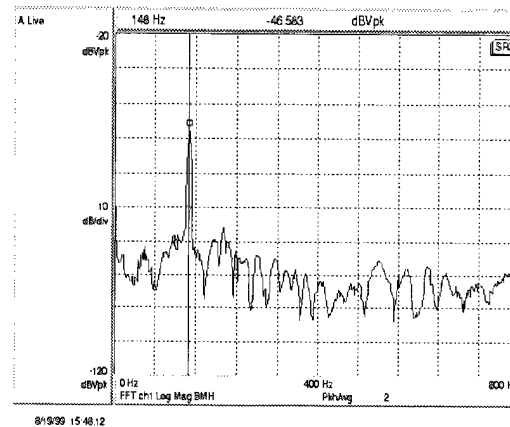
D. Soft hit with a small modal hammer

E. Hard hit with a small modal hammer

Figure 4.1. Vibration spectra generated by various methods of excitation on a flat two-layered graphite/epoxy composite bare-beam specimen (specimen 1A) with simple supports.

A. Fingernail flick

B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet

D. Soft hit with a small modal hammer

E. Hard hit with a small modal hammer

Figure 4.2. Vibration spectra generated by various methods of excitation on a flat two-layered graphite/epoxy composite bare-beam specimen (specimen 1B) with simple supports.

Figures 4.3 and 4.4 record the vibration spectra of two simply-supported flat near-symmetric graphite/epoxy composite bare-beam specimens (specimens 2A and 2B, respectively) subjected to free vibrations generated by five different methods of mechanical excitation. Table 4.2 lists the fundamental frequency data for the two simply-supported flat near-symmetric bare-beam specimens, which are accompanied with these spectra shown in figures 4.3 and 4.4. From table 4.2, we observe, as before, that the fundamental frequency results are essentially the same with different methods of mechanical excitation and their specimen-to-specimen variations are negligibly small. From table 4.2, we also see that the average of the experimental data on the two near-symmetric specimens is calculated as 244.6 Hz.

Table 4.2. Fundamental frequency (Hz) data of flat *near-symmetric* graphite/epoxy composite bare-beam specimens with simple supports.

| Methods of Mechanical Excitation	Specimen 2A	Specimen 2B
Fingernail Flick	246	244
Large Rubber Mallet—Soft Hit	244	246
Large Rubber Mallet—Hard Hit	244	242
Small Modal Hammer—Soft Hit	246	246
Small Modal Hammer—Hard Hit	244	244

Average Data = 244.6 Hz

Based on the above two average experimental data on the flat two-layered and near-symmetric bare-beams, we can calculate the relative fundamental frequency, α, of the simply-supported flat two-layered graphite/epoxy composite bare-beam (vs. the near-symmetric composite bare-beam) as

$$\alpha = 149.4/244.6 = 0.611. \tag{4.1}$$

In other words, the fundamental frequency of a flat near-symmetric graphite/epoxy composite bare-beam with simple supports can be substantially reduced (i.e., by 38.9%) by replacing the near-symmetric composite with the two-layered cross-ply laminate. This clearly demonstrates that the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate substantially reduces the fundamental frequency of the flat near-symmetric composite bare-beam with simple supports.

We now compare the theoretical predictions made by the available analytical solutions derived by Tang (1996) with the average experimental data (shown above) on the fundamental frequency and the relative fundamental frequency of the flat cross-ply laminated bare-beam specimens with simple supports. Toward this aim, let b stand for the length and t stand for the thickness of the flat bare-beam (i.e., the cross-ply laminated composite beam). Let ρ_0, E_{11}, and E_{22}, respectively, denote the mass density, the ply Young's modulus in the fiber direction, and the ply Young's modulus in the direction transverse to the fiber direction of the cross-ply laminated composite. If all these geometric and material quantities are known, then the cyclic fundamental (natural) frequency (in cycle/s or Hertz), f, of the flat cross-ply laminated bare-beam with simple supports can be calculated by the following formula:

$$f = \frac{\omega_1}{2\pi} = \frac{\pi}{4\sqrt{3}} \frac{t}{b^2} \sqrt{\frac{E_{11}\gamma(1-3\beta^2)}{\rho_0}}, \tag{4.2}$$
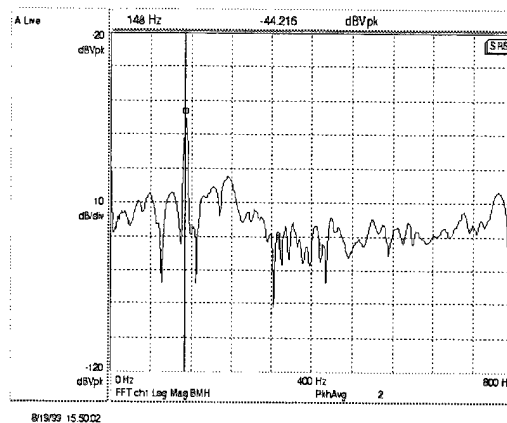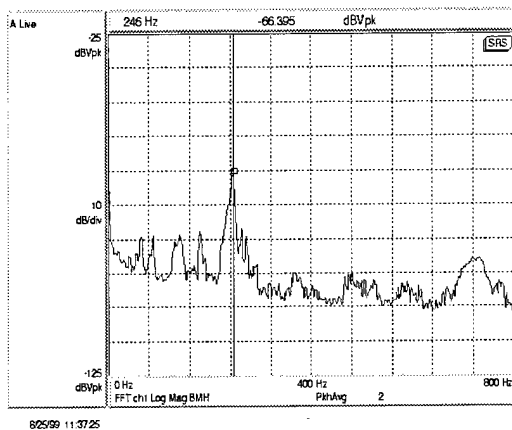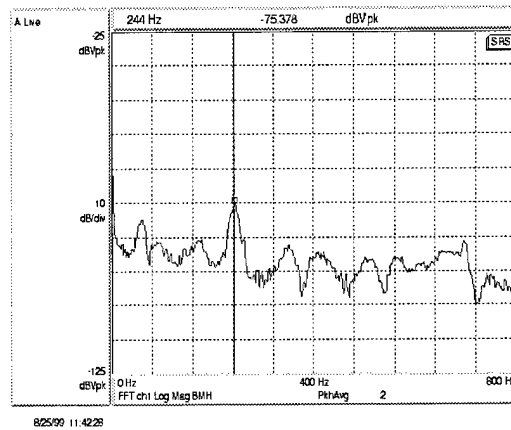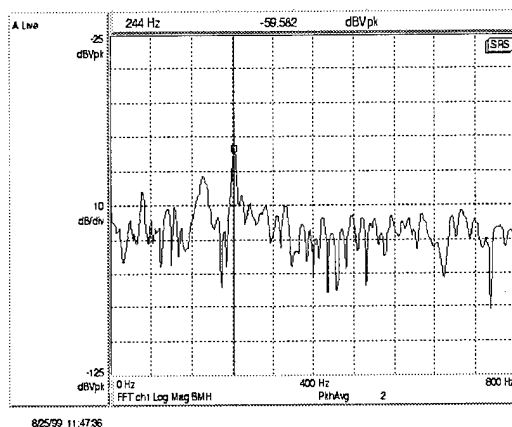
24

A. Fingernail flick

B. Soft hit with a large rubber mallet

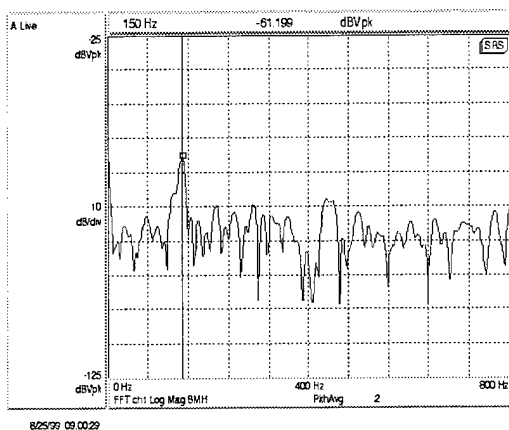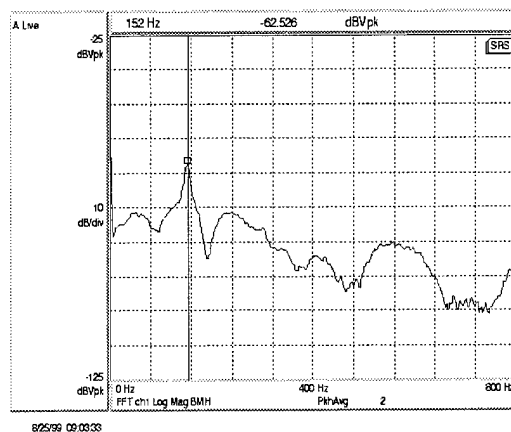C. Hard hit with a large rubber mallet
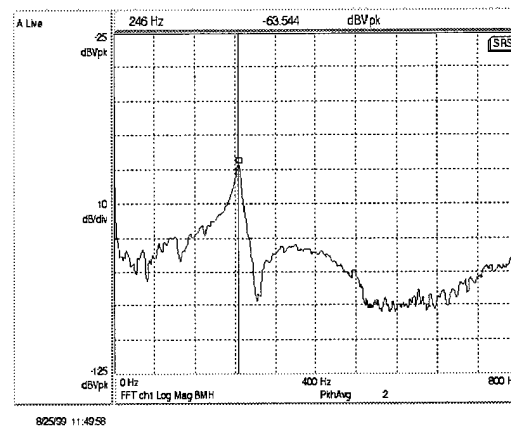
D. Soft hit with a small modal hammer
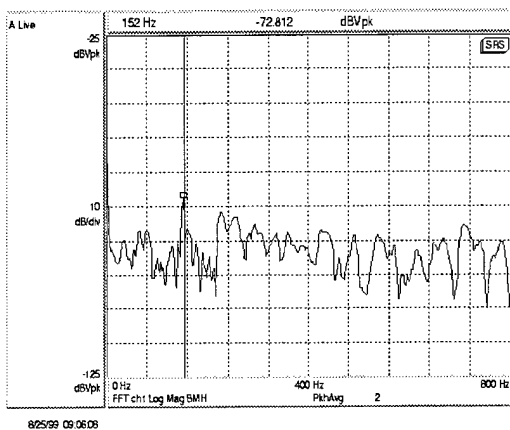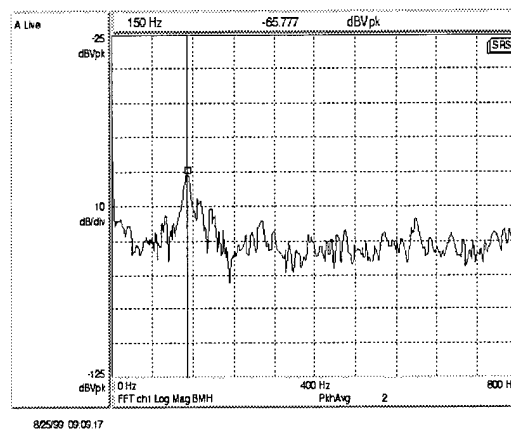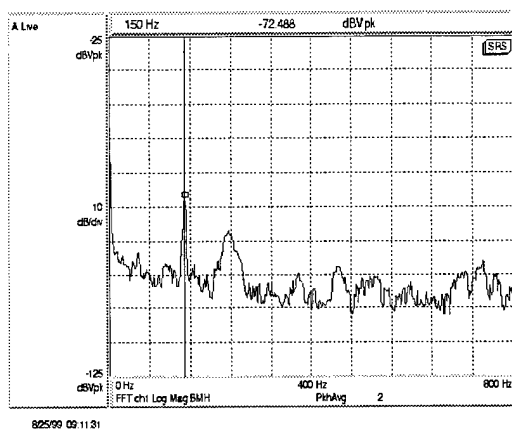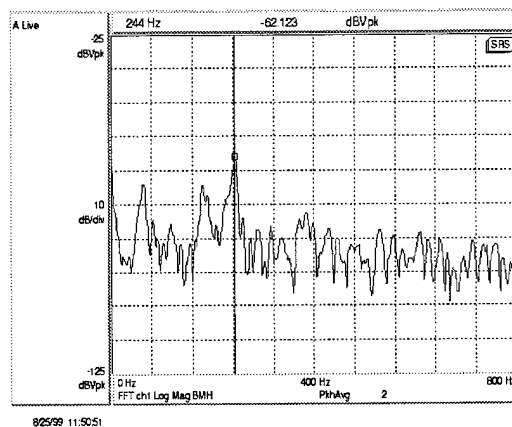

E. Hard hit with a small modal hammer

Figure 4.3. Vibration spectra generated by various methods of excitation on a flat near-symmetric graphite/epoxy composite bare-beam specimen (specimen 2A) with simple supports.
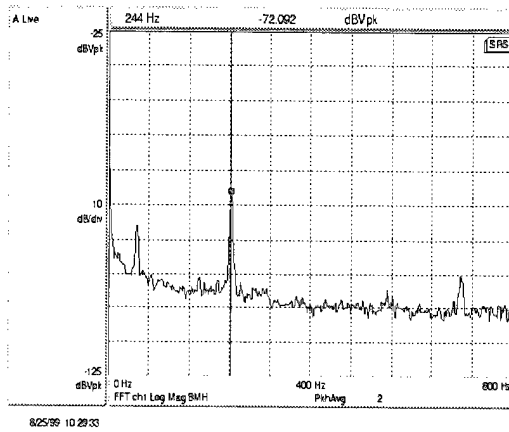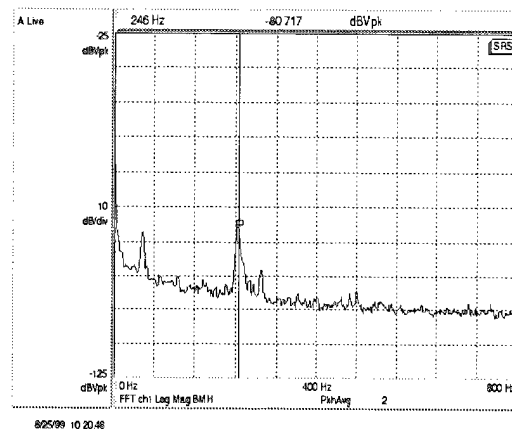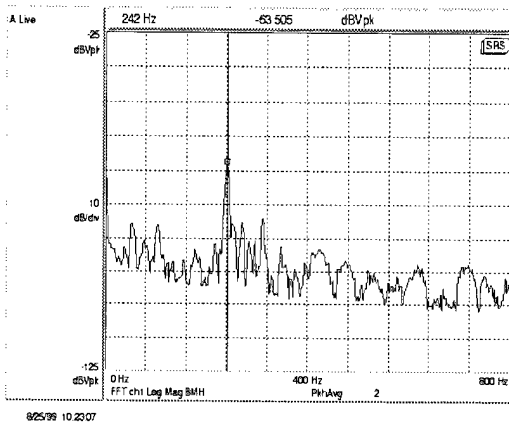
A. Fingernail flick

B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet
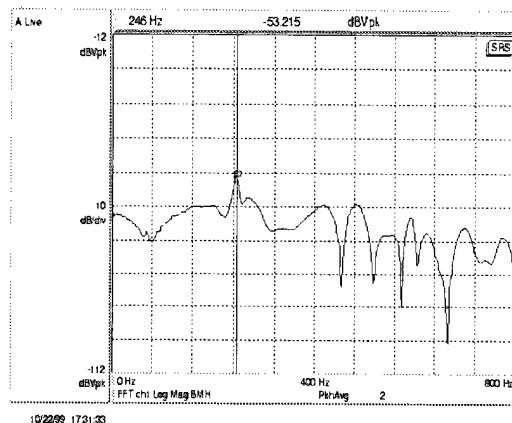
D. Soft hit with a small modal hammer
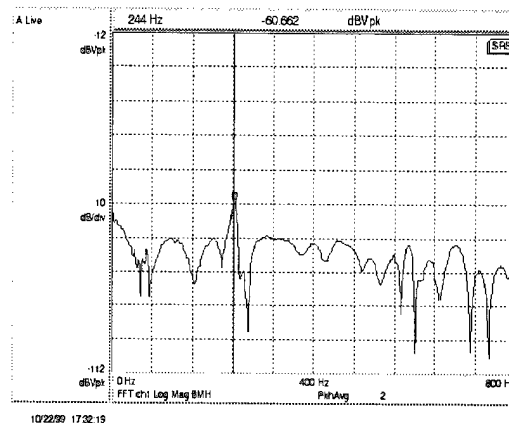
E. Hard hit with a small modal hammer

Figure 4.4. Vibration spectra generated by various methods of excitation on a flat near-symmetric graphite/epoxy composite bare-beam specimen (specimen 2B) with simple supports.

where ω_1 is the radial fundamental (natural) frequency (in radian/s) and its expression can be readily obtained from eq. (57) of Tang (1996), with the help of eqs. (43), (58), and (59) of Tang (1996), and the fact that the actuator/beam thickness ratio, H, of a bare-beam is zero. In eq. (4.2), the expressions for γ and β are given by

$$\gamma = \frac{1+F}{2}, \qquad \beta = \frac{1-F}{N(1+F)}, \tag{4.3}$$

where N is number of layers of the laminate ($N = 2$ and ∞ for two-layered and near-symmetric cross-ply laminates, respectively), and

$$F = \frac{E_{22}}{E_{11}}. \tag{4.4}$$

For the flat bare-beam being tested (see table 2.1),

$$b = 10", \qquad t = 0.2". \tag{4.5}$$

For the graphite/epoxy cross-ply laminate being fabricated,[*] the weight density, γ_0, and the ply moduli, E_{11} and E_{22}, are

$$\gamma_0 = 0.057 \text{ lb/in}^3, \qquad E_{11} = 20 \text{ Msi}, \qquad E_{22} = 1.0 \text{ Msi}, \tag{4.6}$$

which can be obtained from Vinson and Sierakowski (1986). Substitutions of eqs. (4.5) and (4.6) into eqs. (4.4), (4.3), and (4.2) lead to

$$f = 150 \text{ Hz} \tag{4.7}$$

for the flat two-layered bare-beam and

$$f = 242 \text{ Hz} \tag{4.8}$$

for the flat near-symmetric bare-beam, respectively. Using eqs. (4.7) and (4.8), we obtain the relative fundamental frequency, α, of the simply-supported flat two-layered composite beam (vs. the near-symmetric composite beam) as

$$\alpha = 150 / 242 = 0.620. \tag{4.9}$$

Table 4.3 summarizes the comparisons of the theoretical predictions and the above average experimental data on the fundamental frequency and the relative fundamental frequency of simply-supported flat two-layered and near-symmetric graphite/epoxy composite bare-beam specimens. From this table, we see that the differences for all comparisons are less than 1.47%.[**] Clearly, the

---

[*] The moduli data used here are slightly different from the tensile moduli data ($E_{11} = 18.5$ Msi, $E_{22} = 0.8$ Msi) obtained from the rudimentary stiffness tests conducted in (Dinges, 1997) (see the footnote of section 2.4). The latter set of data was not used because it unexpectedly yielded substantial (i.e., 15 to 30%) specimen-to-specimen variations, which were not consistent with very little specimen-to-specimen variations observed in the fundamental frequency data. The high specimen-to-specimen variations yielded in the moduli data might result from the use of a miscalibrated test machine for measuring the specimen displacements in the stiffness tests.

[**] In other words, the average experimental data are within 1.45% of the theoretical predictions.

theory-experiment comparisons are excellent for the flat graphite/epoxy cross-ply laminated bare-beam specimens in the simply-supported boundary conditions.

Table 4.3. Comparisons of the theoretical predictions and the (average) experimental data on the fundamental frequency and the relative fundamental frequency of flat graphite/epoxy cross-ply laminated bare-beam specimens with simple supports.

		Prediction	Experiment	Difference
Fundamental Frequency	Two-Layered	150.0 Hz	149.4 Hz	0.40%
	Near-Symmetric	242.0 Hz	244.6 Hz	−1.06%
Relative Fundamental Frequency		(150.0/242.0 =) 0.620	(149.4/244.6 =) 0.611	1.47%

4.1.2. Flat and Free-Free Supported

Figures 4.5 and 4.6 record the vibration spectra of two flat two-layered graphite/epoxy composite bare-beam specimens (specimens 1A and 1B, respectively) with free-free supports and subjected to free vibrations generated by five different methods of mechanical excitation. Table 4.4 lists the fundamental frequency data for the two free-free supported flat two-layered bare-beam specimens, which are accompanied with these spectra shown in figures 4.5 and 4.6. From table 4.4, we observe that the fundamental frequency results are identical for each specimen under different methods of mechanical excitation, and their specimen-to-specimen variations are negligibly small. From table 4.4, we also see that the average experimental data on the two two-layered specimens is 330.0 Hz.
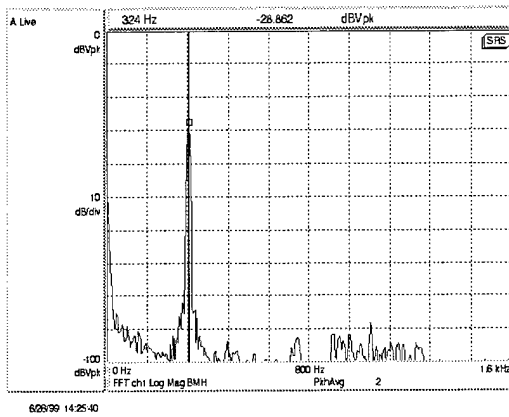
A. Fingernail flick
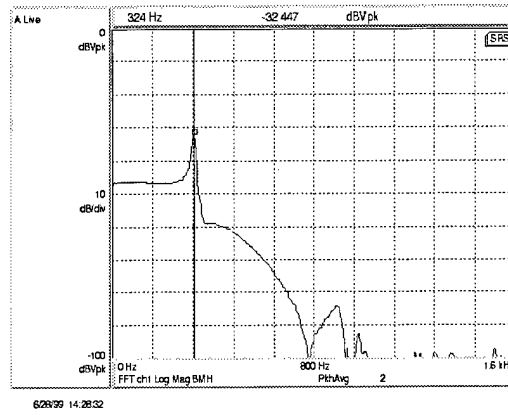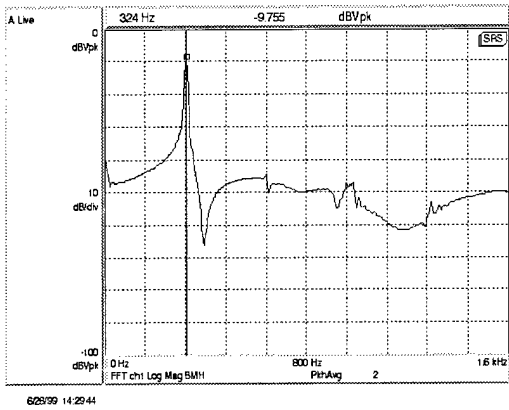
B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet

D. Soft hit with a small modal hammer

E. Hard hit with a small modal hammer

Figure 4.5. Vibration spectra generated by various methods of excitation on a flat two-layered graphite/epoxy composite bare-beam specimen (specimen 1A) with free-free supports.

29

A. Fingernail flick

B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet

D. Soft hit with a small modal hammer

E. Hard hit with a small modal hammer

Figure 4.6. Vibration spectra generated by various methods of excitation on a flat two-layered graphite/epoxy composite bare-beam specimen (specimen 1B) with free-free supports.

Table 4.4. Fundamental frequency (Hz) data of flat *two-layered* graphite/
epoxy composite bare-beam specimens with free-free supports.

Methods of Mechanical Excitation	Specimen 1A	Specimen 1B
Fingernail Flick	324	336
Large Rubber Mallet—Soft Hit	324	336
Large Rubber Mallet—Hard Hit	324	336
Small Modal Hammer—Soft Hit	324	336
Small Modal Hammer—Hard Hit	324	336

Average Data = 330.0 Hz

Figures 4.7 and 4.8 record the vibration spectra of two flat near-symmetric graphite/epoxy composite bare-beam specimens (specimens 2A and 2B, respectively) with free-free supports and subjected to free vibrations generated by five different methods of mechanical excitation. Table 4.5 lists the fundamental frequency data for the two free-free supported flat near-symmetric bare-beam specimens, which are accompanied with these spectra shown in figures 4.7 and 4.8. From table 4.5, we observe, as before, that the fundamental frequency results are essentially the same with different methods of mechanical excitation, and their specimen-to-specimen variations are negligibly small. From table 4.5, we also see that the average experimental data on the two near-symmetric specimens is 536.8 Hz.

Table 4.5. Fundamental frequency (Hz) data of flat *near-symmetric* graphite/epoxy composite bare-beam specimens with free-free supports.

Mechanical Excitation	Specimen 2A	Specimen 2B
Fingernail Flick	540	532
Large Rubber Mallet—Soft Hit	540	532
Large Rubber Mallet—Hard Hit	540	536
Small Modal Hammer—Soft Hit	540	536
Small Modal Hammer—Hard Hit	540	532

Average Data = 536.8 Hz

Based on the above stated average experimental data on the flat two-layered and near-symmetric bare-beams, we can calculate the relative fundamental frequency, α, of the free-free supported flat two-layered graphite/epoxy composite bare-beam (vs. the near-symmetric composite bare-beam) as

$$\alpha = 330.0/536.8 = 0.615. \qquad (4.10)$$

In other words, the fundamental natural frequency of a flat near-symmetric graphite/epoxy composite bare-beam with free-free supports can be substantially reduced (by 38.5%) by replacing the near-symmetric composite with the two-layered cross-ply laminate. This clearly demonstrates that the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate substantially reduces the fundamental frequency of the flat near-symmetric bare-beam with the free-free supports.
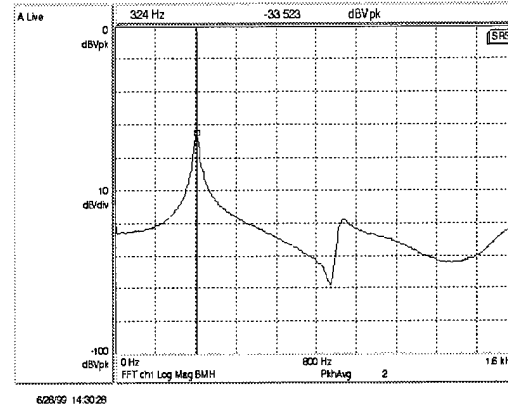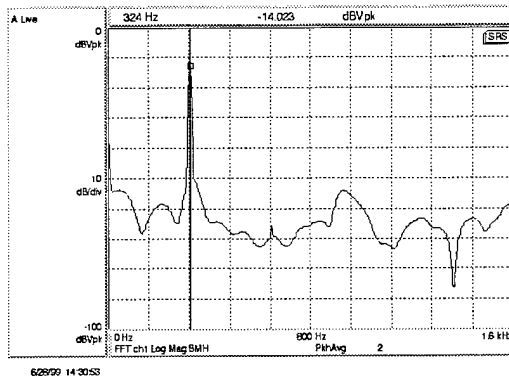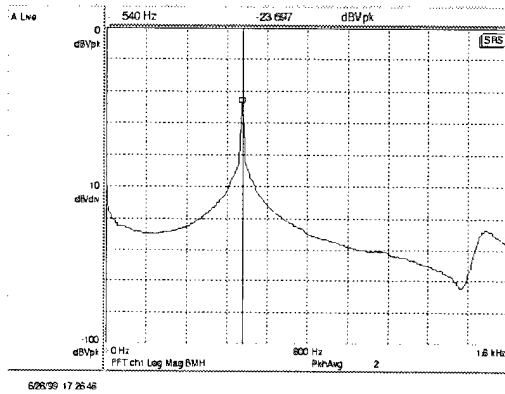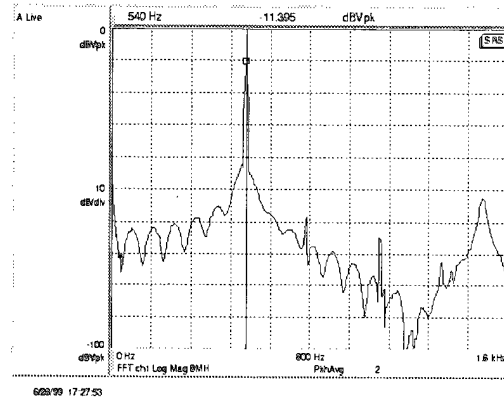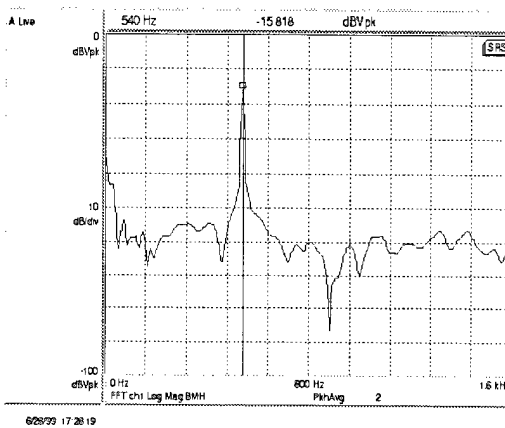
A. Fingernail flick

B. Soft hit with a large rubber mallet
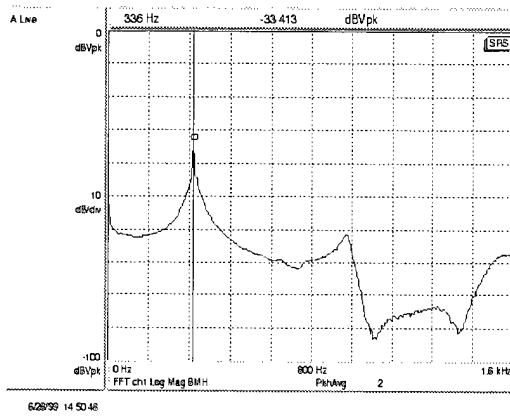

C. Hard hit with a large rubber mallet

D. Soft hit with a small modal hammer

E. Hard hit with a small modal hammer

Figure 4.7. Vibration spectra generated by various methods of excitation on a flat near-symmetric graphite/epoxy composite bare-beam specimen (specimen 2A) with free-free supports.

A. Fingernail flick

B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet
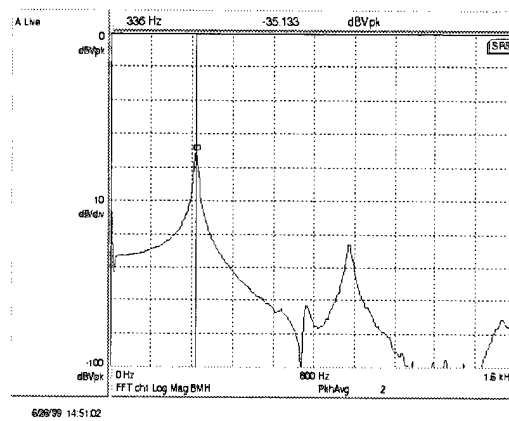

D. Soft hit with a small modal hammer
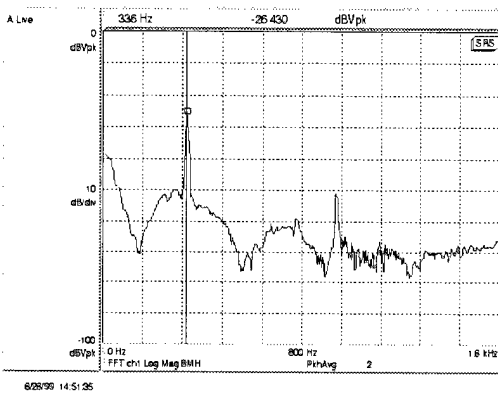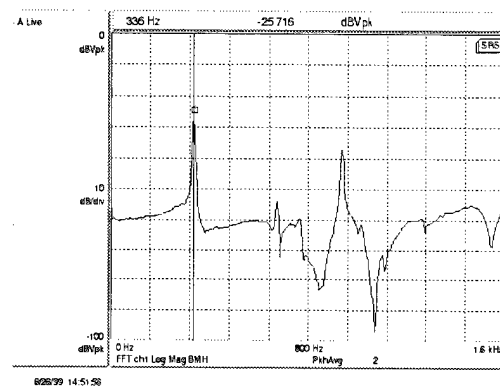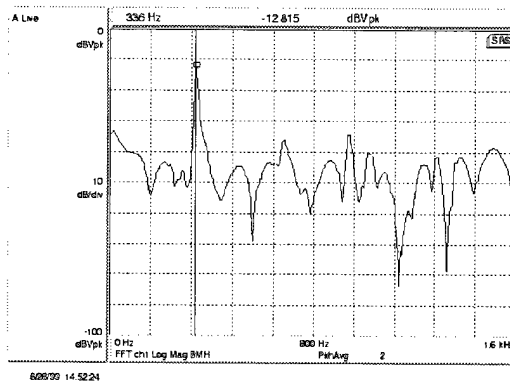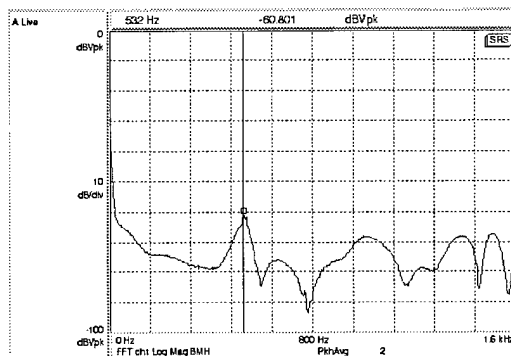

E. Hard hit with a small modal hammer

Figure 4.8. Vibration spectra generated by various methods of excitation on a flat near-symmetric graphite/epoxy composite bare-beam specimen (specimen 2B) with free-free supports.

Moreover, a direct comparison of eq. (4.10) with eq. (4.1) clearly indicates that the b-e coupling effect on the fundamental frequency reduction of the flat near-symmetric bare-beam is practically the same, whether the beam is vibrated in the simply-supported or the free-free supported boundary conditions. This free-free supported vs. simply-supported comparison in the (average) experimental data on the relative fundamental frequency of flat bare-beam specimens is also listed in table 4.6 for subsequent reference. Furthermore, by comparing eq. (4.10) with eq. (4.9), we see that all the (average) experimental data obtained on the relative fundamental frequency of the free-free supported flat bare-beam are within 0.81% of the prediction with the available analytical solutions for a simply-supported flat bare-beam.

Table 4.6. Comparison of the (average) experimental data on the relative fundamental frequency of free-free supported flat and curved bare-beam specimens with that of simply-supported flat ones.

	Fundamental Frequency (Hz)		Relative Fundamental Frequency	
	Two-Layered	Near-Symmetric	Free-Free Supported	Difference (vs. 0.611 for Simply-Supported Flat Bare-Beam)
Flat Bare-Beam	330.0	536.8	(330.0/536.8 =) 0.615	0.65%
Curved Bare-Beam	238.0	386.0	(238.0/386.0 =) 0.617	0.98%

4.1.3. Curved and Free-Free Supported

Figure 4.9 records the vibration spectra of a curved two-layered graphite/epoxy composite bare-beam specimen (specimen 7A) with free-free supports and subjected to free vibrations generated by five different methods of mechanical excitation. Table 4.7 lists the fundamental frequency results for the free-free supported curved two-layered bare-beam specimen, which are accompanied with these spectra shown in figure 4.9. From table 4.7, we observe that the fundamental frequency results are identical for the specimen under different methods of mechanical excitation, with the average experimental result being 238.0 Hz.
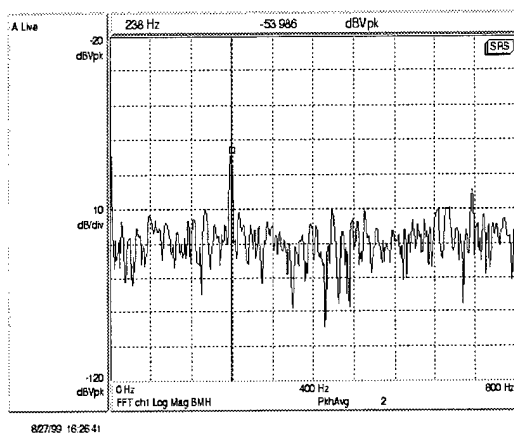
A. Fingernail flick
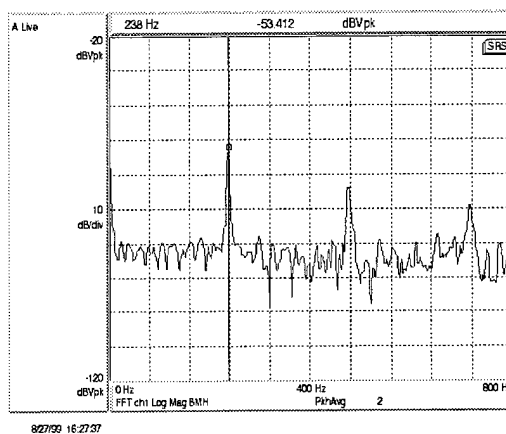
B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet

D. Soft hit with a small modal hammer

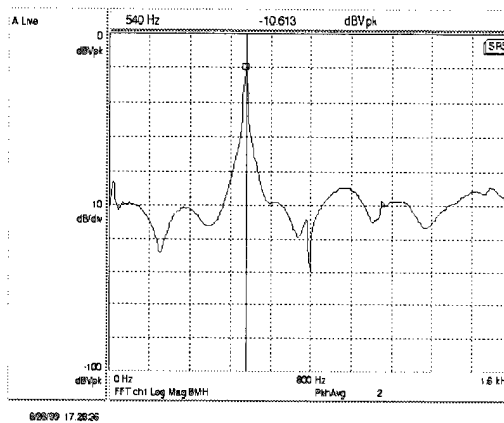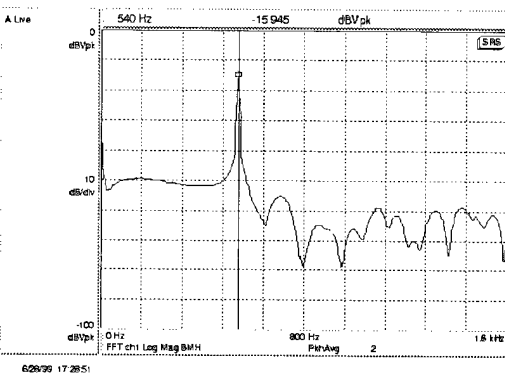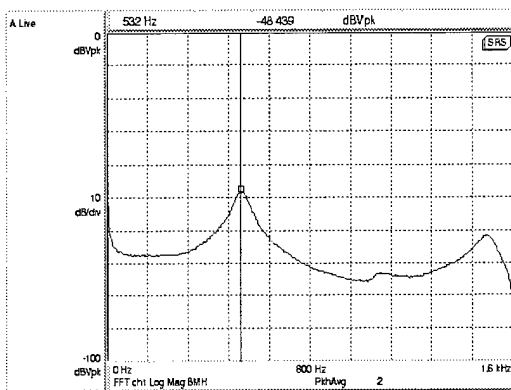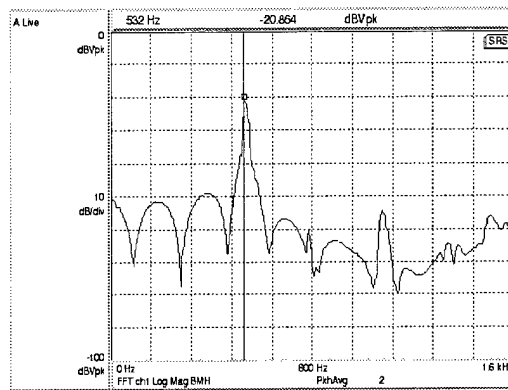E. Hard hit with a small modal hammer

Figure 4.9. Vibration spectra generated by various methods of excitation on a curved two-layered graphite/epoxy composite bare-beam specimen (specimen 7A) with free-free supports.

Table 4.7. Fundamental frequency (Hz) data of a curved *two-layered* graphite/epoxy composite bare-beam specimen with free-free supports.

Methods of Mechanical Excitation	Specimen 7A
Fingernail Flick	238
Large Rubber Mallet—Soft Hit	238
Large Rubber Mallet —Hard Hit	238
Small Modal Hammer—Soft Hit	238
Small Modal Hammer—Hard Hit	238

Average Data = 238.0 Hz

Figures 4.10 and 4.11 record the vibration spectra of two curved near-symmetric graphite/epoxy composite bare-beam specimens (specimens 8A and 8B, respectively) with free-free supports and subjected to free vibrations generated by five different methods of mechanical excitation. Table 4.8 lists the fundamental frequency data for the two free-free supported curved near-symmetric bare-beam specimens, which are shown with these spectra in figures 4.10 and 4.11. From table 4.8, we observe that the fundamental frequency results are the same for each specimen under different methods of mechanical excitation, and their specimen-by-specimen variations are negligibly small. Table 4.8 also shows that the average experimental data on the two near-symmetric specimens is 386.0 Hz.

Table 4.8. Fundamental frequency (Hz) data of curved *near-symmetric* graphite/epoxy composite bare-beam specimens with free-free supports.

Methods of Mechanical Excitation	Specimen 8A	Specimen 8B
Fingernail Hit	384	388
Large Rubber Mallet—Soft Hit	384	388
Large Rubber Mallet—Hard Hit	384	388
Small Modal Hammer—Soft Hit	384	388
Small Modal Hammer—Hard Hit	384	388

Average Data = 386.0 Hz

Based on the above stated average experimental data on the curved two-layered and near-symmetric bare-beams, we can calculate the relative fundamental frequency, α, of the free-free supported curved two-layered graphite/epoxy composite bare-beam (vs. the near-symmetric composite bare-beam) as

$$\alpha = 238.0/386.0 = 0.617. \tag{4.11}$$

In other words, the fundamental natural frequency of a free-free supported curved near-symmetric graphite/epoxy composite bare-beam can be substantially reduced (by 38.3%) by replacing the near-symmetric composite with the two-layered cross-ply laminate. This clearly demonstrates that the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate substantially reduces the fundamental frequency of the curved near-symmetric composite bare-beam with free-free supports.
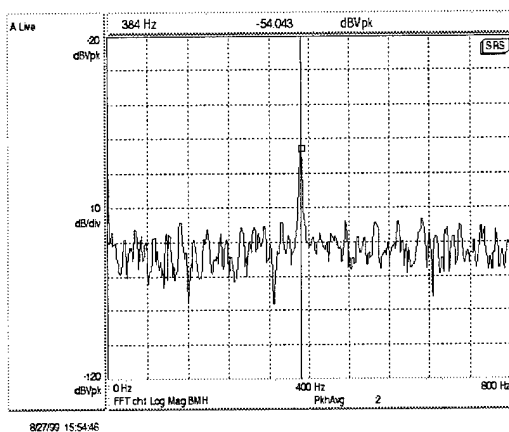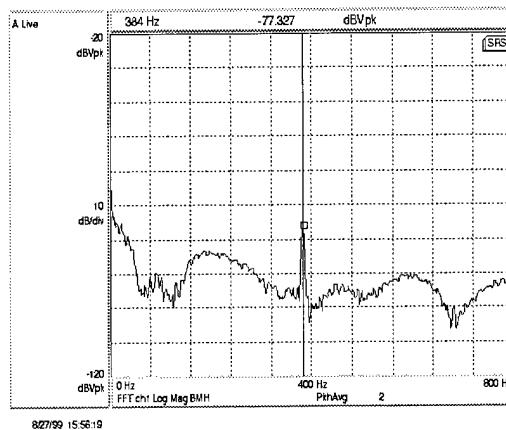
A. Fingernail flick

B. Soft hit with a large rubber mallet
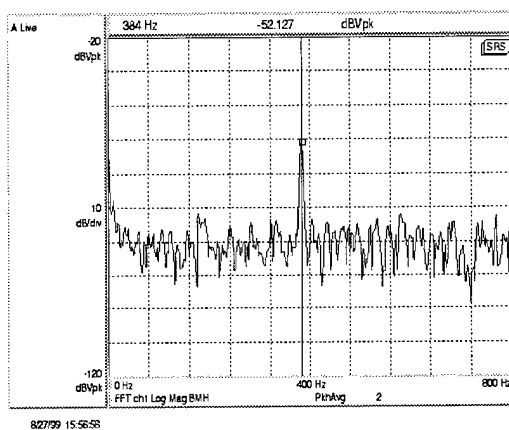
C. Hard hit with a large rubber mallet
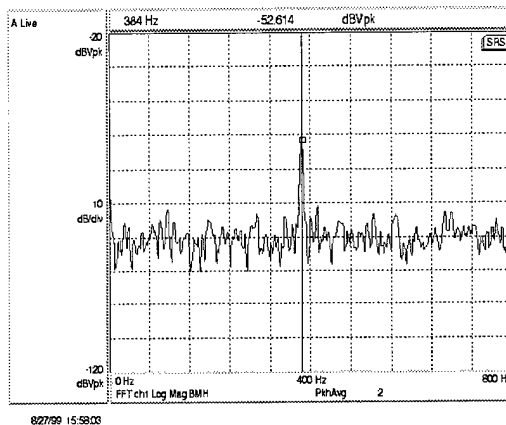
D. Soft hit with a small modal hammer
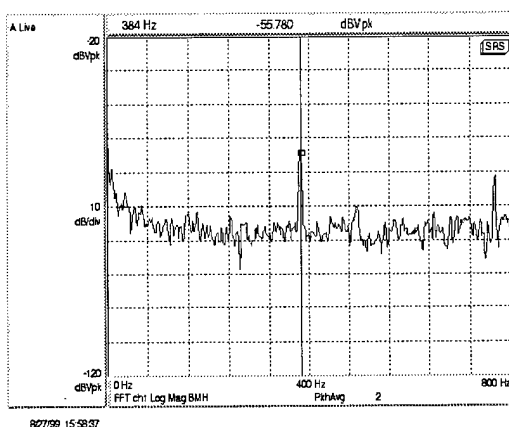
E. Hard hit with a small modal hammer

Figure 4.10. Vibration spectra generated by various methods of excitation on a curved near-symmetric graphite/epoxy composite bare-beam specimen (specimen 8A) with free-free supports.
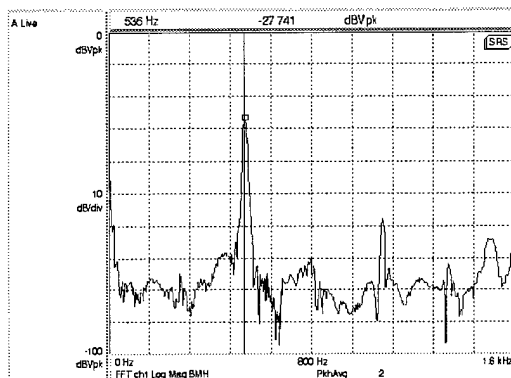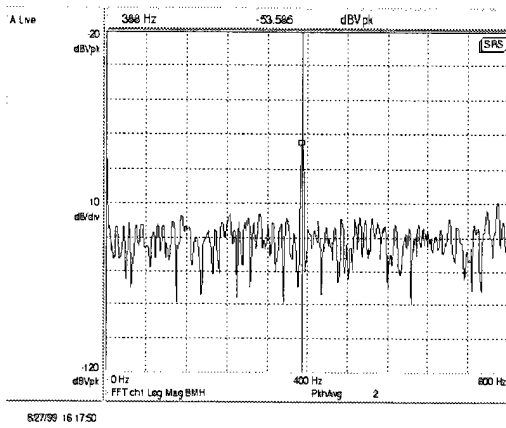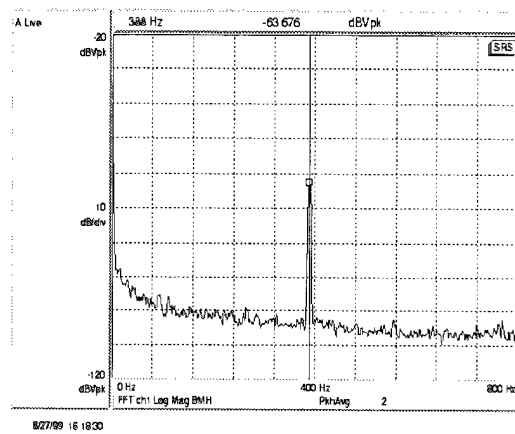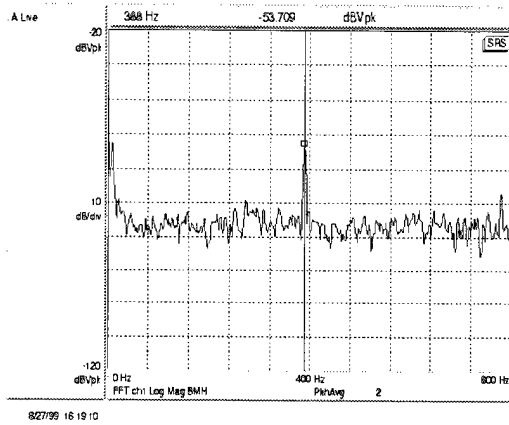
A. Fingernail flick

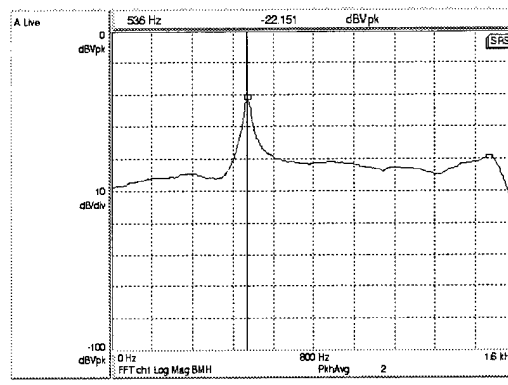B. Soft hit with a large rubber mallet

C. Hard hit with a large rubber mallet
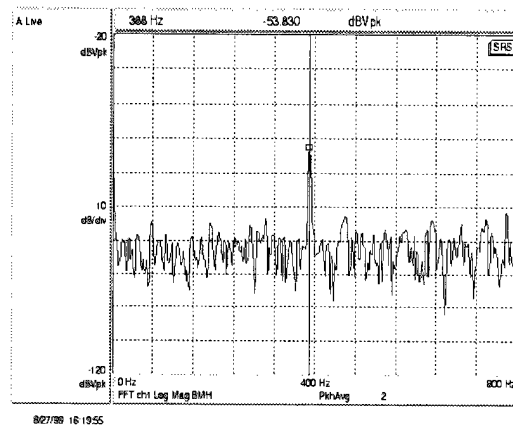
D. Soft hit with a small modal hammer
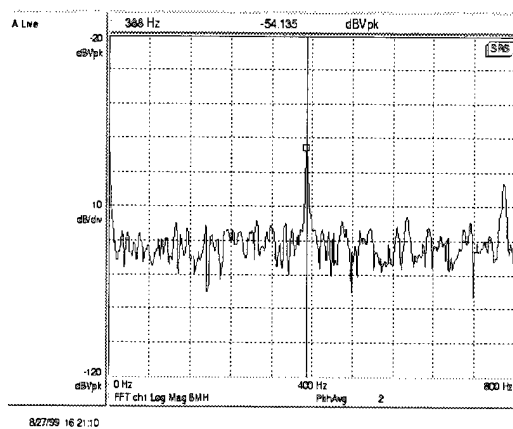
E. Hard hit with a small modal hammer

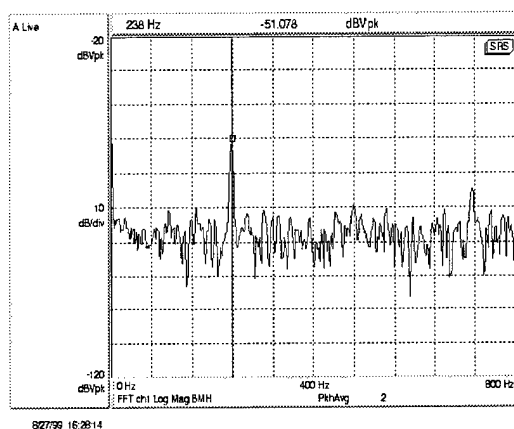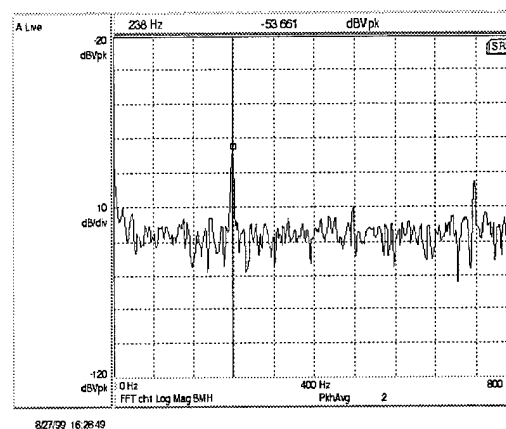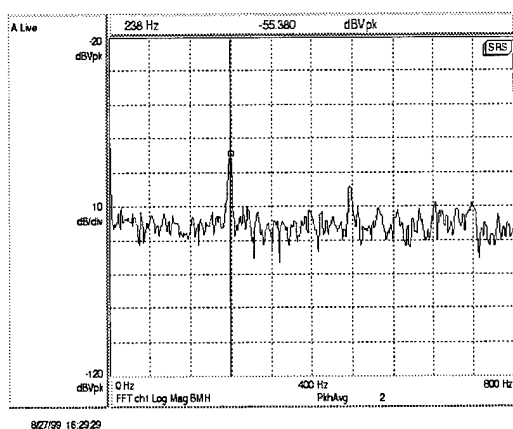Figure 4.11. Vibration spectra generated by various methods of excitation on a curved near-symmetric graphite/epoxy composite bare-beam specimen (specimen 8B) with free-free supports.

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Moreover, direct comparisons of eq. (4.11) with eqs. (4.10) and (4.1) clearly indicate that the b-e coupling effect on the fundamental frequency reduction for the free-free supported curved near-symmetric bare-beam is nearly identical to that for the free-free supported flat near-symmetric bare-beam, and is practically the same as that for the flat near-symmetric bare-beam in the simply-supported boundary conditions. This curved vs. flat comparison in the (average) experimental data on the relative fundamental frequency of bare-beam specimens was also listed in table 4.6. Furthermore, by comparing eqs. (4.1), (4.10), and (4.11) with eq. (4.9), we find that all the average experimental data obtained on the relative fundamental frequency of flat and curved bare-beam specimens are within 1.45% of the prediction with the available analytical solutions for a flat bare-beam with simple supports. This finding seems to suggest that the theoretical predictions made by the available analytical solutions or the experimental data for the relative fundamental frequency of simply-supported flat bare-beams could be used to estimate the relative fundamental frequency of the free-free supported pertaining flat and curved bare-beams.

4.2. ACTUATOR-BEAMS

Unlike bare-beam specimens, only a few actuator-beam specimens yielded good data, whereas the rest may need to be refabricated and retested due to suspected poor bonding (at testing) between the actuator and the composite of these specimens. Only the data on the fully-bonded specimens are worth recording in this preliminary report. Subsection 4.2.1 starts with the theoretical predictions on the fundamental frequency and the relative fundamental frequency for all flat actuator-beams with simple supports. These predictions then provide the basis for the suspected poor bonding of the specimens. Finally, the forced vibration data on the flat fully-bonded actuator-beam specimens tested in the simply-supported boundary conditions are recorded and compared with theoretical predictions made by SSC San Diego with available analytical solutions. Subsections 4.2.2 and 4.2.3 detail the forced vibration data on the flat and curved fully-bonded actuator-beam specimens, respectively, tested in the free-free boundary conditions.

4.2.1. Flat and Simply-Supported

To pave the way for the theoretical predictions of the fundamental frequency and the relative fundamental frequency of a flat actuator-beam with simple supports, it is natural to present the pertaining formula first. Toward this aim, let t_a, ρ_0^a, and E_{11}^a designate the thickness, mass density, and Young's modulus in the fiber direction, respectively, of the actuator in the actuator-beam. If all these geometric and material quantities for the actuator and those (i.e., b, t, ρ_0, E_{11}, and E_{22}) for the cross-ply laminated composite of the actuator-beam are known, then the cyclic fundamental (natural) frequency (in Hertz), f, of the flat cross-ply laminated actuator-beam with simple supports can be calculated by the following formula:

$$f = \frac{\omega_1}{2\pi} = \frac{\pi}{4\sqrt{3}} \frac{t}{b^2} \sqrt{\frac{E_{11}}{\rho_0} \frac{\lambda_1}{\lambda_3}}, \tag{4.12}$$

where ω_1 is the radial fundamental (natural) frequency (in radian/s) and its expression can be obtained readily from eq. (57) of Tang (1996), using eqs. (43), (58), and (59) of Tang (1996). In eq. (4.12), the expressions for λ_1 and λ_3 are given by

$$\lambda_1 = \lambda_2 + \gamma^2 G^2 (1 - 3\beta^2) - 6\beta\gamma GH(H + 1), \tag{4.13}$$
$$\lambda_3 = G(\gamma G + H)(HI + 1),$$

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where

$$\lambda_2 = H[H^3 + 2\gamma G(2H^2 + 3H + 2)],$$

$$G = \frac{E_{11}}{E_{11}^a}, \qquad H = \frac{t_a}{t}, \qquad I = \frac{\rho_o^a}{\rho_0}. \tag{4.14}$$

For the flat actuator-beam being tested, as listed in table 2.1,

$$t_a = 0.1", 0.2". \tag{4.15}$$

For the PZT actuator, the weight density, γ_0^a, and the Young's modulus in the fiber direction are

$$\gamma_0^a = 0.2739\,\text{lb/in}^3, \qquad E_{11}^a = 10.15\,\text{Msi}, \tag{4.16}$$

which can be obtained from Newnham et al. (1992). Substitutions of eqs. (4.5) and (4.6) for the laminate properties and eqs. (4.15) and (4.16) for the actuator properties into eqs. (4.4), (4.3), (4.14), (4.13), and (4.12) lead to the desired theoretical predictions of the fundamental frequency and the relative fundamental frequency of the actuator-beams. These theoretical predictions are recorded in table 4.9.

Table 4.9. Predictions of the fundamental frequency and the relative fundamental frequency of flat graphite/epoxy cross-ply laminated bare-beam[*] and actuator-beam specimens with simple supports.

Actuator/Beam Thickness Ratio, H	Fundamental Frequency, f		Relative Fundamental Frequency, α
	Two-Layered	Near-Symmetric	
0.0	150 Hz	242 Hz	0.620
0.5	165 Hz	239 Hz	0.690
1.0	222 Hz	281 Hz	0.790

The flat actuator-beam specimens with near-symmetric cross-ply laminate (specimens 4A, 4B, 6A, and 6B) were planned in the entire experimental program as the benchmark specimens, because this type of specimen has been used in the industry for a long time with predictable behaviors. More precisely, the data obtained on the fundamental frequency of these flat actuator-beam specimens were expected to be very close to their theoretical predictions listed in table 4.9. However, to our surprise, the data were systematically 10 to 25% below their predicted values, based on the assumption made in section 2.1 of Tang (1996) that the actuator had to be fully bonded to the composite laminate.

Such systematic errors prompted our suspicions that the actuators of these actuator-beam specimens at testing were probably poorly bonded to their respective composite laminates, thus reducing the dynamically "effective" thickness and "effective" stiffness of the specimens, and consequently reducing their fundamental frequency data. The suspected poor bonding in these specimens might have resulted from poor initial bonding of the actuator-segments subassemblies to their composite laminates with unfilled room-temperature-cure, two-part epoxy,[**] and/or from bond-loss due to aging

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[*] The predictions for the bare-beams (i.e., $H = 0$) reported earlier in eqs. (4.7), (4.8), (4.9) are also included here in table 4.9 for an easy reference.

[**] For a detailed description of the actuator-beam fabrication, refer to section 2.3.

deterioration of the epoxy in the specimens fabricated many years ago (e.g., FY 96), and/or due to rough specimen handling, etc., before testing.

Poor bonding was also suspected to exist at testing in specimen 5A (a flat two-layered actuator-beam), specimens 9A, 9B, and 10B (curved two-layered actuator-beams), and specimen 12A (a curved near-symmetric actuator-beam). SDSU has graciously agreed to find a good student to refabricate and retest all suspected poorly-bonded flat and curved actuator-beam specimens. In the interim, we recorded the data obtained only from the fully-bonded specimens, specimen 3A and 5B (flat two-layered actuator-beams), specimen 11A (a curved two-layered actuator-beam), and specimens 10A and 12B (curved near-symmetric actuator-beams).* We also compared some of these data with theoretical predictions made by available analytical solutions.

Figure 4.12 depicts the vibration spectra generated by electrical excitation on simply-supported flat two-layered graphite/epoxy composite actuator-beam specimens, specimen 3A (with an actuator/ beam thickness ratio of 0.5) and specimen 5B (with an actuator/beam thickness ratio of 1.0). Along with the vibration spectra in figure 4.12, their respective fundamental frequencies are also shown. Table 4.10 lists the fundamental frequency data for the two simply-supported flat two-layered composite actuator-beam specimens.
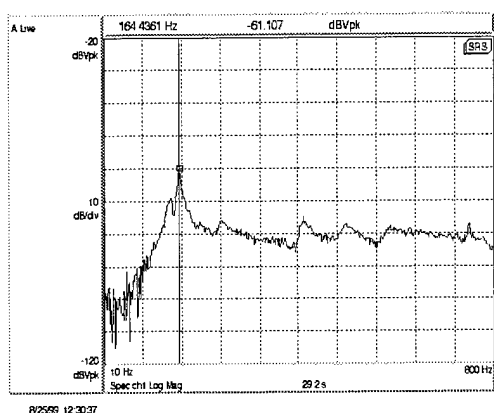
A. Specimen 3A with an actuator/beam thickness ratio of 0.5
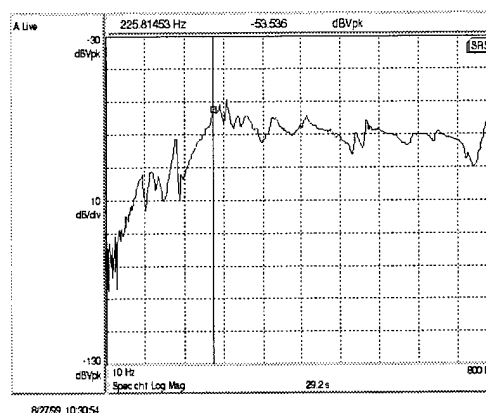
B. Specimen 5B with an actuator/beam thickness ratio of 1.0

Figure 4.12. Vibration spectra generated by electrical excitation on simply-supported flat two-layered graphite/epoxy composite actuator-beam specimens.

Table 4.10. Fundamental frequency data of *simply-supported* flat *two-layered* graphite/epoxy composite actuator-beam specimens subjected to electrical excitation.

Specimen No.	Actuator/Beam Thickness Ratio, H	Fundamental Frequency, f
3A	0.5	164 Hz
5B	1.0	226 Hz

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* Thus, only 5 of 14 total fabricated actuator-beam specimens (see section 2.4) were considered fully-bonded. The remaining 9 were suspected to be poorly-bonded.

Table 4.11 compares theoretical predictions and experimental data on the fundamental frequency of two simply-supported flat two-layered graphite/epoxy cross-ply laminated actuator-beam specimens (specimens 3A and 5B). From table 4.11, we see that the differences for the two comparisons are less than 1.77%.[*] Clearly, the theory-experiment comparisons are excellent for the simply-supported flat graphite/epoxy cross-ply laminated actuator-beam specimens.

Table 4.11. Comparisons of theoretical predictions and experimental data on the fundamental frequency of flat graphite/epoxy two-layered composite actuator-beam specimens with simple supports.

Specimen No.	Actuator/Beam Thickness Ratio, H	Fundamental Frequency, f		
		Prediction	Experiment	Difference
3A	0.5	165 Hz	164 Hz	0.61%
5B	1.0	222 Hz	226 Hz	−1.77%

4.2.2. Flat and Free-Free Supported

Figure 4.13 records the vibration spectra generated by electrical excitation on free-free supported flat two-layered graphite/epoxy composite actuator-beam specimens, specimen 3A (with an actuator/beam thickness ratio of 0.5) and specimen 5B (with an actuator/beam thickness ratio of 1.0). Table 4.12 lists the fundamental frequency data on the two free-free supported flat two-layered actuator-beam specimens, which are accompanied with the spectra.
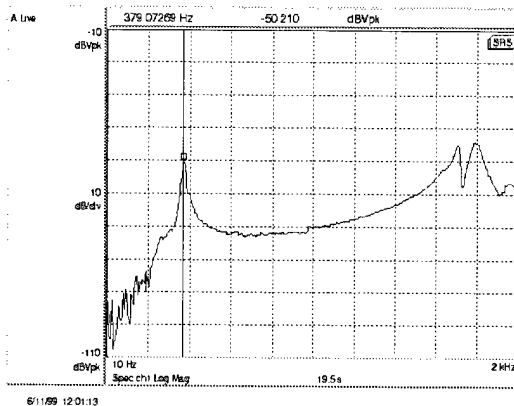
A. Specimen 3A with an actuator/beam thickness ratio of 0.5
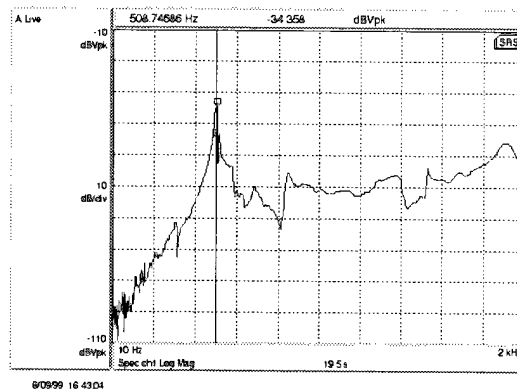
B. Specimen 5B with an actuator/beam thickness ratio of 1.0

Figure 4.13. Vibration spectra generated by electrical excitation on free-free supported flat two-layered graphite/epoxy composite actuator-beam specimens.

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[*] In other words, the average experimental data are within 1.80% of the theoretical predictions.

Table 4.12. Fundamental frequency data of *free-free supported* flat *two-layered* graphite/epoxy composite actuator-beam specimens subjected to electrical excitation.

Specimen No.	Actuator/Beam Thickness Ratio, H	Fundamental Frequency, f
3A	0.5	379 Hz
5B	1.0	509 Hz

4.2.3. Curved and Free-Free Supported

Figure 4.14 records the vibration spectrum generated by electrical excitation on a free-free supported curved near-symmetric graphite/epoxy composite actuator-beam specimen (specimen 10A) with an actuator/beam thickness ratio of 0.5. Figure 4.15 records the vibration spectra generated by electrical excitation on two free-free supported curved graphite/epoxy cross-ply laminated actuator-beam specimens, specimen 11A (with the two-layered composite) and specimen 12B (with the near-symmetric composite), having an actuator/beam thickness ratio of 1.0. Table 4.13 lists the fundamental frequency data for the three free-free supported curved actuator-beam specimens, which are accompanied with the spectra shown in figures 4.14 and 4.15.
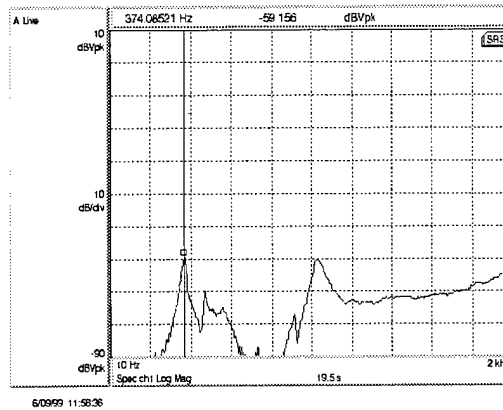
Figure 4.14. Vibration spectrum generated by electrical excitation on a free-free supported curved near-symmetric graphite/epoxy composite actuator-beam specimen (specimen 10A) with an actuator/beam thickness ratio of 0.5.
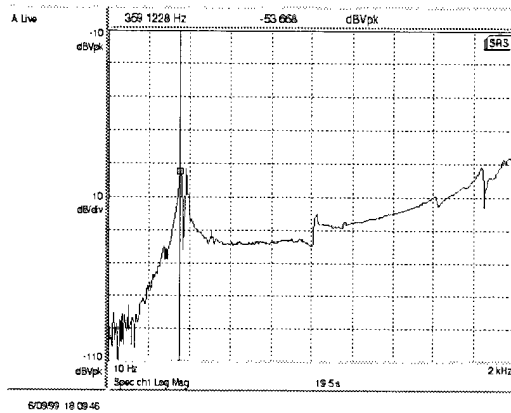
A. Specimen 11A with two-layered composite   B. Specimen 12B with near-symmetric composite
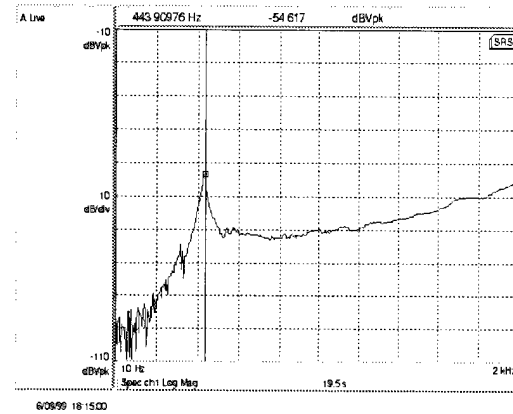
Figure 4.15. Vibration spectra generated by electrical excitation on free-free supported curved graphite/epoxy cross-ply laminated actuator-beam specimens with an actuator/beam thickness ratio of 1.0.

Table 4.13. Fundamental frequency data of *free-free supported* curved graphite/epoxy cross-ply laminated actuator-beam specimens subjected to electrical excitation.

Specimen No.	Actuator/Beam Thickness Ratio, H	Composite	Fundamental Frequency, f
10A	0.5	Near-Symmetric	374 Hz
11A	1.0	Two-Layered	359 Hz
12B	1.0	Near-Symmetric	444 Hz

Based on the experimental data listed in table 4.13 for the curved two-layered and near-symmetric actuator-beam specimens with an actuator/beam thickness ratio of 1.0 (specimens 11A and 12B, respectively), we can calculate the relative fundamental frequency, α, of the free-free supported curved two-layered graphite/epoxy composite actuator-beam with an actuator/beam thickness ratio of 1.0 (vs. the pertaining near-symmetric composite actuator-beam) as

$$\alpha = 359 / 444 = 0.808. \tag{4.17}$$

In other words, the fundamental natural frequency of a free-free supported curved near-symmetric graphite/epoxy composite actuator-beam with an actuator/beam thickness ratio of 1.0 can be substantially reduced (by 19.2%) by replacing the near-symmetric composite with the two-layered cross-ply laminate. This clearly demonstrates that the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate substantially reduces the fundamental frequency of the free-free supported curved near-symmetric actuator-beam with a thickness ratio of 1.0.

In table 4.9, the theoretical prediction for the relative fundamental frequency, α, of the simply-supported flat two-layered graphite/epoxy composite actuator-beam with an actuator/beam thickness ratio of 1.0 has been obtained as

$$\alpha = 222 / 281 = 0.790. \tag{4.18}$$

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A direct comparison of eq. (4.17) with eq. (4.18) clearly indicates that the experimental data obtained on the relative fundamental frequency of the free-free supported curved actuator-beam with an actuator/beam thickness ratio of 1.0 is within 2.28% of the prediction made by the available analytical solutions for a simply-supported flat actuator-beam with the same actuator/beam thickness ratio. This comparison is also recorded in table 4.14. Moreover, this comparison and the excellent theory-experiment comparisons made in subsection 4.2.1 seem to suggest that the theoretical predictions made by the available analytical solutions or the experimental data for the relative fundamental frequency of simply-supported flat actuator-beams could be used to estimate the relative fundamental frequency of the free-free supported pertaining curved actuator-beams.

Table 4.14. Comparison of the relative fundamental frequency of the experimental data of *free-free supported curved* actuator-beam specimens with an actuator/beam thickness ratio of 1.0 and the prediction for *simply-supported flat* actuator-beam specimens with the same actuator/beam thickness ratio.

Relative Fundamental Frequency		
Free-Free Supported, Curved Actuator-Beam (Experiment)	Simply-Supported, Flat Actuator-Beam (Prediction)	Difference
(359 / 444 =) 0.808	(222 / 281 =) 0.790	2.28%

5. SUMMARY AND CONCLUSIONS

The super composite beam and split cylinder experiments conducted so far have been documented in this preliminary report. These experiments were planned by SSC San Diego with the following two principal objectives: (1) explore and demonstrate the bending-extension (b-e) coupling effect of graphite/epoxy two-layered cross-ply laminate for potentially substantial improvements (e.g., substantial reductions in fundamental (natural) frequencies) of low-frequency, wall-driven composite projectors, such as the slotted cylinder projector; (2) provide experimental data to confirm theoretical predictions (with analytical solutions previously developed by SSC San Diego [Tang, 1995a, 1995b, 1996]) on b-e coupled composite beams with simple supports.

Table 2.1 listed the planned flat and curved (i.e., 180° split circular cylindrical shell) shapes of bare-beam and actuator-beam specimens for fabrication, using graphite/epoxy two-layered and near-symmetric cross-ply laminates. The basic flat laminated beam had nominal dimensions of 10" (length) x 1.65" (width) x 0.2" (thickness), while the basic curved laminated beam had an inner radius of 3.18", width of 1.65", and thickness of 0.2". The bare-beams were basic laminated beams without any actuator bonded to them. The flat actuator-beams were fabricated from the basic flat laminated beams with a PZT (PZT-4) actuator fully bonded (at room temperature) to one side of the 0° layer of the beams in two actuator/beam thickness ratios of 0.5 and 1.0. The curved actuator-beams were fabricated from the basic curved laminated beams with a PZT (PZT-4) actuator fully bonded (at room temperature) to the concave side of the 0° layer of the curved beams in two actuator/beam thickness ratios of 0.5 and 1.0. Clearly, it was planned to have a total of 12 groups of specimens. With two duplicates for each group, the total number of planned specimens was 24. SDSU was contracted to fabricate the specimens. Using the methods described in sections 2.2 and 2.3, SDSU was able to fabricate 21 specimens as listed in table 2.2 and shown in figure 2.3. These specimens consisted of 7 (4 flat and 3 curved) bare-beams and 14 (7 flat and 7 curved) actuator-beams.

Free vibration tests on the fabricated bare-beams and forced vibration tests on the actuator-beams were jointly conducted by SSC San Diego and SDSU in 1999 in the High Voltage and Materials Testing Laboratory of SSC San Diego. Free vibrations were generated by five different methods of mechanical excitation: fingernail flick, soft and hard hits with a large rubber mallet, and soft and hard hits with a small modal hammer. Forced vibration was generated by electrical excitation of the PZT actuator bonded to the specimen. Moreover, all flat specimens were tested in both the simply-supported and the free-free boundary conditions (see figures 3.6 and 3.7), whereas all curved specimens were tested only in the free-free boundary conditions (see figure 3.8), due to the setup of the current testing fixtures for simple supports. Furthermore, the free and forced vibration testing results on the fundamental frequency of the specimens were measured by the Fast Fourier Transform (FFT) measuring group and the Swept Sine measuring group, respectively, of the SRS Model SR780 network signal analyzer.

Excellent data were obtained from all bare-beam specimens:

a. The fundamental frequency data are essentially independent of the above-mentioned five different mechanical excitation methods, and their specimen-to-specimen variations are negligibly small.

b. With simple supports, the average experimental data on the fundamental frequency and the relative fundamental frequency obtained from the flat specimens are within 1.45% of the theoretical predictions made by SSC San Diego with previously derived analytical solutions (see table 4.3).

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c. With free-free supports, the average experimental data on the relative fundamental frequency obtained from the flat and curved specimens are nearly identical; also, they are practically the same (with a maximum difference of 0.98%) as data obtained from the simply-supported flat specimens (see table 4.6). This and the result stated in item b above seem to suggest that the theoretical predictions made by the available analytical solutions or the experimental data for the relative fundamental frequency of simply-supported flat bare-beams could be used to estimate the relative fundamental frequency of the free-free supported pertaining flat and curved bare-beams.

d. All experimental data clearly demonstrate that the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate substantially reduces the fundamental frequency of near-symmetric composite specimens. More specifically, the reduction is
38.9% for simply-supported flat specimens (see eq. (4.1)),
38.5% for free-free supported flat specimens (see eq. (4.10)), and
38.3% for free-free supported curved specimens (see eq. (4.11)).

Unlike bare-beam specimens, only a few (5 out of 14) actuator-beam specimens yielded reportable data, whereas the rest might have to be refabricated and retested due to suspected poor bonding between the actuator and the composite of these specimens (as explained in subsection 4.2.1). Fortunately, from the five fully-bonded specimens, excellent data were obtained:

a. With simple supports, the experimental data on the fundamental frequency of two flat two-layered cross-ply laminated actuator-beams with different actuator/beam thickness ratios are within 1.80% of the theoretical predictions made by SSC San Diego with previously derived analytical solutions (see table 4.11).

b. With free-free supports, the experimental data on the relative fundamental frequency of two curved actuator-beam specimens with an actuator/beam thickness ratio of 1.0 clearly demonstrate that the b-e coupling effect of graphite/epoxy two-layered cross-ply laminate substantially reduces (by 19.2%) the fundamental frequency of near-symmetric specimens (see eq. (4.17)); also, the relative fundamental frequency data is within 2.28% of the prediction with the available analytical solutions for simply-supported flat actuator-beams with an actuator/beam thickness ratio of 1.0 (see table 4.14). This and the result stated in item a above seem to suggest that the theoretical predictions made by the available analytical solutions or the experimental data for the relative fundamental frequency of simply-supported flat actuator-beams could be used to estimate the relative fundamental frequency of the free-free supported pertaining curved actuator-beams.

Based on the above summarized results of all bare-beam and five fully-bonded actuator-beam specimens, the following conclusions can be drawn:

a. The bending-extension (b-e) coupling effect of graphite/epoxy two-layered cross-ply laminate has the potential to substantially reduce (by 20 to 40%) the fundamental frequencies of low-frequency, wall-driven composite projectors, such as the slotted cylinder projector.

b. The experimental data have confirmed the theoretical predictions, made with analytical solutions previously derived by SSC San Diego, for b-e coupled composite beams with simple supports.

To further reinforce these conclusions, we want to pursue the following tasks:

a. Refabricate and retest the suspected poorly-bonded specimens to confirm the poor-bonding suspicion and provide more reliable and useful data.

b. Conduct finite-element analyses on the free-free supported flat and curved shapes of bare-beam and actuator-beam specimens to correlate their theoretical predictions and experimental data.

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14. ABSTRACT

The subject experiments had two main objectives: (1) explore and demonstrate whether the bending-extension (b-e) coupling effect of graphite/epoxy two-layered cross-ply laminate can substantially improve (reduce fundamental natural frequencies of) low-frequency, wall-driven composite projectors (such as the slotted cylinder projector), and (2) provide experimental data to confirm theoretical predictions (made with previously derived analytical solutions) on b-e coupled composite beams with simple supports. To achieve these objectives, a total of 21 flat and curved shapes of bare-beam and actuator-beam specimens, respectively, were fabricated and tested in free and forced vibrations under simply-supported and/or free-free boundary conditions. Excellent experimental data on fundamental frequencies were obtained for all seven bare-beam specimens and five fully-bonded actuator-beam specimens. These data remarkably confirmed the theoretical predictions for simply-supported flat bare-beam and actuator-beam specimens, with less than 2.0% differences between the data and the predictions. These data also clearly demonstrated the bending-extension coupling effect, yielding the following substantial reduction in fundamental frequency: (a) 38.9%, 38.5%, and 38.3%, respectively, for simply-supported flat, free-free supported flat, and free-free supported curved bare-beam specimens; (b) 19.2% for free-free supported curved actuator-beam specimens with an actuator/beam thickness ratio of 1.0.

15. SUBJECT TERMS

Mission Area: Ocean Surveillance

cross-ply laminated composite	bending-extension coupling	forced/free vibration	slotted cylinder projector
fundamental frequency	actuator	actuator-beam	wall-driven projector

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